

1 How is strain localized in a meta-granitoid, mid-crustal basement  
2 section? Spatial distribution of deformation in the central Aar  
3 massif (Switzerland)

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19 Keywords: strain, localization, mid-crustal, shear zone, granitoid, Alpine

## 25    **Abstract**

26        This study investigates strain distribution in granitoid rocks formerly in the middle  
27    crust in the Central Aar massif, Switzerland and places the deformation behavior in the  
28    tectonic framework of the Alpine orogeny. Strain is heterogeneously distributed in terms  
29    of strain partitioning forming several hundreds of closely spaced shear zones (SZ) (>80  
30    SZ/km with SZ thicknesses <10 cm; about 10 SZ/km with SZ thicknesses of 0.5-10 m)  
31    separating 3D bodies of low to moderate background strain. Both the degree of  
32    background-strain intensity as well as the number of shear zones increases from granitic  
33    to granodioritic host rocks and is controlled by primary variations in the mica content  
34    between 10-15 vol% (granodiorite) and <8 vol% (granite). Shear zones evolved from  
35    ductile shearing in granodiorites, whereas they often nucleated from fractures in the  
36    stronger granites.

37        The majority of the steep shear zones preferentially accommodated upward motion  
38    by the southern Block leading to an increase in peak metamorphic conditions from 250°  
39    in the North to 450°C in the South of the Aar massif. The shear zones initiated at about  
40    18-20 km depths during a stage of crustal thickening (Handegg phase). Subsequent  
41    deformation reactivated some shear zones with a gradual transition from reverse dip-slip  
42    over oblique-slip to strike-slip shear zones under local transpressional conditions  
43    (Oberaar phase).

44

## 1 Introduction

The continental middle crust is mainly built up of polymetamorphic gneisses dissected by magmatic intrusions forming both compositional and mechanical anisotropies at a variety of scales. Therefore deformation tends to be distributed heterogeneously, depending on the effective material properties of the rock types and mechanical boundaries (e.g. Vernon and Flood, 1988). Deformation concentrated in domains with reduced rock strength is called strain localization, where ductile non-coaxial, high strain zones can evolve, which are referred to as shear zones. Information about the geometric, temporal and kinematic relationships of shear zones is essential in understanding finite strain, as well as the deformation history of orogens, thrusts and strike-slip zones (e.g., Ramsay, 1980; Choukroune and Gapais, 1983; Gapais et al., 1987; Marquer et al., 1996; Carreras et al., 2010; Menegon and Pennacchioni, 2010).

During nucleation and evolution of shear zones, two different end-members can be considered: (i) Rheology-dependent localization in a homogeneous material where no pre-existing mechanical anisotropy is present (Mancktelow, 2002), and (ii) reactivation of pre-existing mechanical anisotropies or discontinuities (Guermani and Pennacchioni, 1998; Mancktelow and Pennacchioni, 2005; Pennacchioni, 2005). A current debate is whether such strain localization occurs entirely under viscous conditions (Platt and Behr, 2011; Peters et al., 2016) or requires fractures that act as precursors for the subsequent ductile deformation (Mancktelow and Pennacchioni, 2005; Fousseis et al., 2006; Handy et al., 2007; Pennacchioni and Mancktelow, 2007). In the case of granitoid middle crust, relatively few studies have investigated the link between rock composition and mechanical anisotropies (e.g. Vernon and Flood, 1988; Wintsch et al., 2005). Particularly

the link between the quantitative characterization of strain patterns at the scale of meters versus several kilometers, as stated recently by Horsman et al. (2008) or Raynaud and Vasseur (2014), needs to be further investigated.

We investigate this problem by studying a large segment of exhumed mid-crustal basement rocks at different scales within a total volume of several cubic kilometers. The study area consists of metamorphic and igneous rocks of the Aar massif (southern Haslital, Central Switzerland), which underwent Alpine deformation. Combining field relationships with microstructural investigations, we address questions about how, where and when strain is localized at mid-crustal conditions including the evolution of subsequent exhumation.

## 2 Geological setting

The Aar massif belongs to the External Crystalline Massifs of the Alps and is mainly composed of Paleozoic basement gneisses and migmatites, which were intruded by Variscan and post-Variscan plutons associated with the evolution of Permo-Carboniferous half grabens (Figs. 1 and 2a, Labhart, 1977; Abrecht, 1994; Schaltegger, 1994). Along the Haslital valley, four plutons can be identified (i.e. Mittagflue granite, Central Aar granite, Grimsel granodiorite and Southwestern Central Aar granite, Fig. 2a), which are all of Early Permian age (Schaltegger, 1990).

(INSERT FIGURE 1 HERE)

The pre-Variscan basement rocks are affected by multiple stages of deformation of Proterozoic, Ordovician, to Variscan and finally Alpine age (Stalder, 1964; Steck, 1968; Labhart, 1977; Schaltegger, 1993; Schaltegger et al., 2003). In contrast, the post-



90 Variscan intrusives have only recorded Alpine deformation. For the Haslital, earlier  
91 research suggested an Alpine deformation gradient with both increasing deformation and  
92 metamorphism southward (Choukroune and Gapais, 1983; Bambauer et al., 2005;  
93 Bambauer et al., 2009). From the northern boundary (Innertkirchen) of the Aar massif to  
94 the south (Grimsel Pass), peak Alpine metamorphic conditions increase from lower to  
95 upper greenschist facies (Bambauer et al., 2005; Challandes et al., 2008; Bousquet, 2012;  
96 Goncalves et al., 2012). In light of the structural evolution, different deformation stages  
97 have been suggested for the southern margin of the Aar massif (Steck, 1968).

98 Northwest-directed Alpine thrusting (s1 and stage1, respectively, of Steck, 1968 and  
99 Rolland et al., 2009) led to development of localized high-strain shear zones isolating  
100 lenses of lesser deformation at a variety of scales. In granites of the southern part of the  
101 Haslital, this geometry was referred to as an anastomosing zone pattern (Choukroune and  
102 Gapais, 1983; Marquer et al., 1985; Gapais et al., 1987). Subsequently, this geometrical  
103 relationship has been used in many studies to geometrically describe mid-crustal shear  
104 zones.

105 P-T conditions of the main Alpine deformation in these shear zones reached a  
106 maximum temperature of 450 °C and pressure of 6.5 kbar (Goncalves et al., 2012)  
107 corresponding to depths of ~18-20 km. Deformation is dated at ~22-17 Ma (Challandes  
108 et al., 2008; Rolland et al., 2009) and 13.8-12.2 Ma (Rolland et al., 2009), for a first and a  
109 second stage of ductile shearing, respectively.

### 3 Analytical Methods

Our analysis of strain distribution in the Aar Massif along the Haslital transect involves a detailed study of large-scale (km), meso-scale (m to hundreds of m), handspecimen-scale (cm to dm) and micro-scale (mm) structures. A GIS-based remote-sensing structural map verified by fieldwork, served as the base map. Field relationships and microstructural investigations were used to determine the kinematics and relative ages of structures as well as to interpret the deformation processes.

To quantify the actual rock volume affected by high strain deformation, and to quantify the influence of compositional variations on subsurface deformation, data from the so-called “Transitgas-tunnel” (Schneider, 1974) were also gathered (Fig. 2). These data allow the unique investigation of the spatial and volumetric distribution of brittle and ductile strain in a continuous horizontal transect through a former mid-crustal section. Deformation intensity, as well as the distribution and dimensions (thicknesses) of mylonitic and cataclastic fault zones were quantified along this transect.

To qualitatively describe the degree of deformation on the outcrop scale, we used the foliation intensity, by means of optically visible spacing of sheet silicates and feldspars, in combination with the degree of grain size reduction. Here, the fabric of micas, quartz (size and elongation) and feldspars (size and elongation) was used. At a first glance, changes in foliation intensity and a decrease in grain size correlate directly with strain within a specific rock type, but more care is required when different rock types are compared with each other. We correlated weakly to moderately schistose rocks with very small to small strain intensity, which basically characterizes the background strain in the area. In such tectonites, feldspars have undergone only limited grain-size reduction often

retaining their original magmatic shape. In high strain zones, polymineralic protomylonitic to mylonitic/strongly schistose to ultramylonitic fabrics represent the transition from medium strain over high strain to very high strain, respectively. In these transitions, dramatic changes in shapes and sizes of the mineral grains occur. Particularly the feldspars show a macroscopically visible grain-size reduction and an increase in the grain aspect ratio. Also the quartz aggregates are strongly elongated due to ductile deformation.

We use the orientations of foliations, lineations and shear sense criteria for high-strain shear zones to infer the kinematic framework and its evolution during retrograde cooling and exhumation. Stretching lineations are mostly defined by elongated and dynamically recrystallized quartz aggregates that occur with synkinematic veins of unknown age. We infer that the stretching lineations on these aggregates represent the last increments of ductile strain before the fabric became frozen, rather than the finite strain from the complete deformation history.

## 4 Results

### 4.1 Host rock fabric

All formerly magmatic rocks were deformed and metamorphosed to a variable degree ductilely during Alpine deformation, often developing a pervasive gneissic foliation.

#### 4.1.1 Meta-plutonic rocks

The Mittagflue granite is the northernmost plutonic body (Fig. 2a). Compositionally, the Mittagflue granite is a massive leucocratic granite. Magmatic

feldspars have mm to cm grain sizes, while interstitial quartz aggregates are in the mm-range. The biotite content is around 3 vol% (Schaltegger, 1989; Schaltegger, 1990) and the grain sizes are <5 mm. The Mittagflue granite has little to no internal foliation and is therefore rather isotropic, except at its contacts with neighboring rocks.

To the south, the Central Aar granite is the largest granitic body of the Aar massif and is located in the center of the massif (Fig. 2a). It has a crystallization age of around  $297 \pm 2$  Ma (Schaltegger, 1989; Schaltegger, 1990; Schaltegger and Corfu, 1992). The CAGr has a similar biotite content (4-8 vol%) compared to the Mittagflue granite (Table 1, Fig. 3a). Feldspar grains, biotite grains and quartz aggregates have average sizes <2 cm, <0.5-1 cm and <0.3-0.5 cm, respectively. In most cases, the quartz is entirely dynamically recrystallized ( $\sim 150 \pm 50$   $\mu\text{m}$ ) by subgrain-rotation recrystallization owing to Alpine deformation. Additionally, the CAGr locally has primary magmatic features such as schlieren and mafic enclaves. Aligned magmatic feldspar grains, as well as a shape-preferred orientation of the elongated mafic enclaves, define a primary magmatic foliation, which mostly is parallel to the main NE-SW striking Alpine deformation. The CAGr is cut by late (post-Variscan) aplitic and meta-mafic dykes (Stalder, 1964; Schaltegger, 1990). Alpine background strain is characterized by the alignment of biotite and flattening of interstitial quartz leading to a weakly developed foliation (Fig. 3a).

The Grimsel granodiorite is located further south and is more intensely deformed toward the Grimsel Zone (Fig. 2a). Within error, the granodiorite has the same crystallization age as the CAGr (Schaltegger & Corfu 1992), as corroborated by the mingling structures of GrGr and CAGr related melts. Compositionally, the GrGr is markedly different from the CAGr because it has a greater biotite content of 12-15 vol%

(Table 1, Figs. 3c, 4a). Primary magmatic heterogeneity is stronger in the GrGr and characterized by mafic enclaves, compositional banding and schlieren. Similarly to the CAGr, the GrGr is also cut by aplitic and meta-mafic dykes (Fig. 3g). The grain sizes in domains least affected by Alpine deformation are for feldspars, biotite and dynamically recrystallized quartz, respectively,  $< 2$  cm,  $< 0.5$  mm and  $< 180$   $\mu$ m. Furthermore, the GrGr has a boundary facies along its southern rim, which is defined by an aplitic granite with strong internal heterogeneity (Stalder, 1964; Dollinger, 1989; Schaltegger, 1990). The Alpine background strain is characterized by a variably developed foliation defined by aligned biotite, including locally developed augen-gneiss textures.

The Southwestern Aar granite is the southernmost intrusive rock along the Haslital transect, and equivalent in composition, microstructure as well as age to the CAGr (Fig. 2). To the south, the Southwestern Aar granite is in contact with the Ausserberg-Avat Zone (Stalder, 1964; Schaltegger, 1990). Alpine background strains generally define a weak foliation (Fig. 3i)

#### 4.1.2 Meta-dykes

Aplitic dykes occur more often within the GrGr than the CAGr. Their thicknesses range from cm to several meters. They have clear intrusive contacts and represent late-stage magmatic differentiation within the post-Variscan granitoids (Stalder, 1964; Schaltegger, 1994). The grain sizes of feldspars and quartz are  $< 3$  mm. The dykes are isotropic and have no internal foliation, and are dissected by an intense fracture network near Alpine high-strain zones.

Meta-mafic dykes are numerous in the study area and have partly been classified as meta-lamproids (Oberhänsli, 1986). The contacts between plutonic host rocks and meta-mafic dykes are clear and discrete. Compositionally, they are characterized by a high biotite content (up to 85 vol%, Table 1). The foliation is intense and the grain sizes of mica and feldspars are  $< 50 \mu\text{m}$ . If suitably oriented, the meta-mafic dykes belong to most intensely deformed rock type in the area (Fig. 3h). Some authors postulate that these meta-mafic dykes are unrelated to the post-Variscan granitoid emplacement (Oberhänsli, 1986). However, meta-mafic and aplitic dikes show a geochemical correlation with the granitoids and crosscut the latter (Fig. 3g). Therefore, meta-mafic dykes as well as aplitic dykes are thought to be associated with the latest stages of post-Variscan granitoid emplacement (Schaltegger, 1989).

#### 4.1.3 Polymetamorphic gneisses

The Grimsel Zone (Fig. 2) is defined as the polymetamorphic basement rocks between the GrGr and the Southwestern Aar granite, and is also known as “Gneis-Schiefer-Zwischenzone” (e.g., Stalder, 1964) owing to its limited thickness of  $< 1 \text{ km}$ . Lithologically, the Grimsel Zone is quite heterogeneous, consisting of pre-Variscan metamorphic rocks (i.e., granitoid gneisses and schists, biotite schists, chlorite schists and augen-gneisses, meta-rhyolites). At Grimsel Pass, this zone separates the Southwestern Aar granite from the GrGr (Stalder, 1964; Dollinger, 1989; Abrecht, 1994), and contains a well-developed foliation. Alpine overprint as defined by a new Alpine foliation, shear bands, sheared and/or asymmetrically folded quartz veins as well as opening of young quartz clefts dominates, but locally relicts of less intensely overprinted structures are preserved,

containing a pre-Alpine foliation, which is folded by younger deformation stages (Fig. 3e).

The pre-Variscan basement rocks of the Ausserberg-Avat Zone define the southern boundary of the crystalline Aar massif (Fig. 2). They are composed of augen-gneisses, titanite gneisses, porphyritic gneisses, biotite gneisses and migmatites (Stalder, 1964; Niggli, 1965; Abrecht, 1994). Similarly to the Grimsel Zone, it is difficult to discriminate between pre-Variscan and Alpine deformation due to deformation intensity. (INSERT FIGURES 3, 4 AND 5 HERE)

## 4.2 High strain zones

In the Alpine high-strain zones, ductile and brittle faults both occur. The younger brittle faults contain cataclasites, fault gouges and occasionally fault breccias. A hydrothermal breccia is well-documented at the Grimsel Pass, and partially overprints ductile shear zones (Hofmann et al., 2004; Belgrano et al., 2016).

The ductile shear zones are easily distinguished from their host rocks by greater foliation intensity and much smaller grain size (Fig. 4). Particularly in the intrusive rocks, the original cm-sized magmatic grains are replaced by new grains with sizes of a few micrometers (5-10  $\mu\text{m}$ , Figs. 4, 5). Along with alignment of sheet silicates and compositional banding, well-foliated polymineralic mylonites and ultramylonites occur (Fig. 4). Counting of these shear zones and also cataclastic faults along 12 km of the Transitgas tunnel in the area between Rättrichsbodensee and Grimsel Pass yield 90-125 deformation features per km in the plutonic rocks (Fig. 2b and 6b,c). The high-strain domains, such as cataclasites, mylonites and ultramylonites, range from discrete mm-wide shear zones up to tens of meter wide shear domains with strong strain gradients

traced toward the host rocks. The mm-wide shear zones are most abundant, but typically have limited lateral continuity.

The appearance of the high strain domains depends on the phyllosilicate content (Table 1 and Fig. 3). The number of shear zones and the volume of affected host rock increases toward large-scale lithological contacts, and most notably the contact between the GrGr and Grimsel Zone (Figs. 2a and 6a,c). Also, the 0.5-5 meter wide shear zones increase, from 4 per km to 13 per km to 60 per km from the CAGr to GrGr to Grimsel Zone, respectively (Fig. 6b). Note also that the cataclasites of the Transitgas tunnel mostly overprint mylonitic precursors (Fig. 5). The increase in number, density and thickness of shear zones correlates directly with an increase in mica content (from CAGr to GrGr to Grimsel Zone; Figs. 3 and 6). Furthermore, the volume of the high strain zones increases with greater sheet-silicate content (Table 1 and Figs. 3, 6c). Deformation zones with a limited thickness ( $<0.1$  m) on the other hand, dominate within the post-Variscan intrusives, and most notably within the CAGr (104 shear zones per km).

(INSERT FIGURE 6 HERE)

#### *4.2.1 Alpine deformation structures*

In line with previous studies (Steck, 1968; Rolland et al., 2009), two major phases of localized ductile Alpine deformation can be distinguished by structural orientations (shear plane, stretching lineation), kinematics and crosscutting relationships for the shear zones. We named the two phases the Handegg- and Obergera- phase after their respective type localities. Geometries and strike directions of the corresponding structures are very



consistent in the Aar massif and therefore have a regional significance (Figs. 7, 8). The older phase is named after the locality at Handegg (666'600/162'800), and is characterized by steeply oriented WSW-ENE striking narrow shear zones in the CAGr. The Oberaarsee (660'900/154'475) is the type locality for the younger deformation phase, where a wide system of major strike-slip shear zones of similar orientation is located.

(INSERT FIGURE 7 HERE)

#### 4.2.1.1 Handegg phase

Shear zones belonging to the Handegg phase are identified by their steep lineations (Fig. 2b, 7a, 8, supplementary material Figs. A-C, F). The structures dominantly strike NE-SW to ENE-WSW and dip steeply to the SE, parallel to the foliation in the weakly deformed granitic host rocks. The structures show rather consistent orientations in all domains, except for the Ausserberg-Avat Zone where the shear zones dip steeply towards the NW (Figs. 2b, 8). Variations in dip allow the identification of two sets of shear zones: (i) A major set with dip angles of 65-80° shows reverse sense of shear and (ii) a second set with even steeper dips (80-90°) forming branches that interconnect the major zones (anastomosing shear zones of Choukroune and Gapais, 1983, see also supplementary material Figs. A-C) showing shear senses typical for normal faulting. The number of Handegg-phase shear zones (thickness 0.1-0.5 m) increases from the CAGr to the GrGr, while their spacing decreases, indicating progressive localization of deformation (Figs. 6a, 7a). Stretching lineations are mostly restricted to synkinematic quartz veins, which were affected by dynamic recrystallization. Within the Grimsel Zone (Fig. 7a), later dextral overprinting by the younger Oberaar-

phase deformation is pervasive and therefore Handegg-phase shear zones are not identifiable anymore (Fig. 7b).

#### 4.2.1.2 *Oberaar phase*

The Oberaar phase is dominantly characterized by slightly to moderately east plunging stretching lineations in dynamically recrystallized vein quartz on steeply south-dipping shear planes, indicating dextral oblique- to strike-slip movements (Figs. 2, 7b, 8, supplementary material Figs. D,E,F). Particularly towards the south, a small number of slightly SW to W plunging lineations exist (Fig. 8). Generally, the shear planes have a wide range of strikes from NNE-SSW, E-W to NW-SE (Fig. 9). Cross-cutting relations clearly show that the Oberaar phase structures dissect the Handegg phase structures (Figs. 7a see white arrows; 9a,b; 9e,f; supplementary material Figs. D,E) indicating therefore a younger activity, which was previously observed (Steck 1968; Roland et al. 2009). Based on geometric orientations, the Oberaar-phase shear zones can be further subdivided into: (a) ENE-WSW striking Oberaar<sub>a</sub> orientation; (b) NW-SE striking Oberaar<sub>b</sub> orientation and (c) NE-SW striking Oberaar<sub>c</sub> orientation strike-slip shear zones (Fig. 7b).

Oberaar<sub>a</sub> shear zones dip steeply towards the SE and strike ENE-WSW (Figs. 7b, 9b, supplementary material Fig. D). Commonly they are intensely foliated and have shear bands indicating a dextral sense of shear. Occasionally, E-W to NW-SE striking C' planes are developed, comparable in orientation to the Oberaar<sub>b</sub> structures (Fig. 9a,b). (INSERT FIGURE 9 HERE)

High strain domains related to the Oberaar<sub>a</sub> orientation run along the lithological contact between the GrGr and Grimsel Zone (SZ10 in Table 3; Fig. 7b) and between the

Grimsel Zone and the Southwestern Aar granite (SZ12 in Table 3; Fig. 7b). The Oberaar<sub>a</sub> orientation is dominant within the Grimsel Zone. Detailed mapping at the western end of Oberaarsee and the analysis of a N-S section across the Grimsel Pass shear zone (GPSZ; supplemental material Fig. F) demonstrates the rotation of the old NE-SW striking Handegg-phase foliation (with steep SE down dip lineations) from the rim into the younger ENE-WSW striking shear plane of one branch of the GPSZ related to the Oberaar phase. Note the changes in lineations from down dip to moderate SE plunging into subhorizontal orientation (Fig. 10; see also supplementary material Fig. B(b) and Fig. F). The rotation of both foliation and lineation, as well as the dextral shear sense indicators in the GPSZ, such as dextral C' structures, asymmetric folds and sheared old quartz veins as well as young open quartz clefts (Fig. 10), all support a dextral oblique to strike-slip shearing along the GPSZ (Fig. 10). Note that the range in plunges is also visible for the Oberaar lineations found across the entire study area, and also includes a few additional slight to moderately SW plunging ones (Figs. 2 and 8).

Steeply SW to S dipping and NW-SE to E-W striking Oberaar<sub>b</sub> shear zones are most common in the CAGr (Figs. 2 and 7b, 8). They have a dextral sense of shear, are mostly quite thin (few cm to dm) and clearly crosscut Handegg phase (Fig. 9). Crosscutting relationships with the Oberaar<sub>a</sub> shear zones are contradictory at different scales. While km-scale Oberaar<sub>b</sub> shear zones rotate into the large-scale Oberaar<sub>a</sub> shear zones of the Grimsel Zone (e.g. sz9 and others in Fig. 7b) and do not crosscut the latter, at the outcrop-scale smaller Oberaar<sub>b</sub> shear zones crosscut at some locations Oberaar<sub>a</sub> shear zones. In both cases, however, mylonitic shear zones evolved, which show an identical mineral paragenesis with stable chlorite and white mica but unstable biotite.

338 Obaraar phase shear zones occasionally exploit meta-mafic dykes or run along aplitic  
339 dykes. They have similar orientations to C' structures developed in Obaraar<sub>a</sub> shear zones.  
340 The lineations are dominantly slightly E-ENE plunging, but in few cases slight to  
341 moderately W-NW plunging. This geometry indicates an oblique slip movement with a  
342 strong dominant horizontal component of shear.

343 (INSERT FIGURE 10 HERE)

344 The third orientation (Obaraar<sub>c</sub>) of Obaraar shear zones is characterized by a set of  
345 sinistral shear zones (Figures 2, 3, 7 and 8). Overall, these shear zones strike NNE-SSW  
346 and dip steeply eastwards, but have a limited lateral continuity (Fig. 7b). Furthermore,  
347 their thicknesses do not exceed several tens of cm. They are best preserved in the more  
348 leucocratic rocks, i.e. CAGr and Southwestern Aar granite, although minor Obaraar<sub>c</sub>  
349 zones (thickness < 0.15 m) can also be found within the Grimsel Zone. Given that the  
350 number of these shear zones is rather limited and only very few lineations are found also  
351 point toward a slight oblique slip component (Figs. 2, 8). The mineral stabilities are  
352 identical to those of Obaraar<sub>a</sub> and Obaraar<sub>b</sub> shear zones.

#### 354 4.2.2 *Microstructural characterization*

355 The pre-Alpine (i.e., magmatic) microstructures of the post-Variscan intrusives  
356 consist of large-sized feldspar grains (plagioclase, K-feldspar), biotite and interstitial  
357 quartz. Often a planar fabric consisting of elongated feldspar grains due to magmatic flow  
358 is present (Fig. 11a,b).

359 (INSERT FIGURE 11 HERE)

360 In granitoid domains weakly affected by Alpine deformation, feldspar grains still  
361 retain their magmatic appearance (Fig. 11a). As a consequence of Alpine overprinting,  
362 grain size reduction occurs, where feldspar grains become fragmented by brittle  
363 deformation, together with precipitation of new fine-grained K-feldspar and albite.  
364 Interstitial quartz domains between magmatic feldspars become elongated due to  
365 deformation by intracrystalline plasticity and dynamic recrystallization by subgrain  
366 rotation recrystallization (compare Fig. 11b with 11 d,f). Furthermore, biotite is aligned  
367 subparallel to the macroscopic shear plane (Fig. 11c-f). Occasionally, epidote-filled veins  
368 parallel to the shear plane cut through the magmatic feldspar clasts and recrystallized  
369 quartz aggregates. Along these epidote-filled fractures, ductile micro-shear zones, defined  
370 by quartz and biotite recrystallization, develop (Wehrens et al., in press). With increasing  
371 strain, further grain size reduction accompanied by an increase in mica content is visible.

372 The Handegg-phase shear zones with the steep lineations, and located within the  
373 granites, are mm to several meter thick dark bands of strongly foliated to very fine-  
374 grained mylonitic to ultramylonitic rocks (Fig. 11c,d). The ultramylonitic domains consist  
375 of monomineralic, elongated quartz aggregates (hundreds of  $\mu\text{m}$  wide) and polymineralic  
376 bands (ranging from several  $\mu\text{m}$  up to cm wide, Fig. 11d). Quartz aggregates were  
377 dominantly recrystallized by subgrain rotation recrystallization (Table 4, Fig. 11b).  
378 Recrystallized quartz grain sizes range from 50-200  $\mu\text{m}$ . Polymineralic bands are  
379 characterized by recrystallized K-feldspar, albite, epidote, quartz, biotite and white mica  
380 (Fig. 11d). Pinning of the boundaries of recrystallized grains leads to even smaller grain  
381 sizes (5-50  $\mu\text{m}$ ), compared to those of monomineralic quartz aggregates (Fig. 11d). Some

feldspar grains occur as porphyroclasts, while others undergo grain size reduction, which leads to grain sizes of 500 to 50  $\mu\text{m}$ .

Numerous shear zones from the Oberaar phase within the Grimsel Zone have mineral assemblages comparable to Handegg phase (Fig. 11e,f, Table 4). The Oberaar-phase shear zones within the post-Variscan intrusive rocks locally increase white mica content toward shear-zone centers, creating interconnected bands of pure but extremely fine-grained newly crystallized white mica (Fig. 11h).

Biotite is occasionally replaced by chlorite in rim regions of such shear zones. Biotite-stable conditions are present during both deformation stages. However, retrogression, and the associated reaction of biotite to chlorite, is restricted to the Oberaar-phase shear zones. Also, the appearance of white mica-rich domains result from retrograde mineral assemblages (Fig. 11 g,h). The retrograde mineral assemblage in the Oberaar phase-related microstructures is of lower temperature nature (Table 3).

## 5 Discussion

Our work demonstrates that deformation at mid-crustal levels, as observed at the southern rim of the Aar massif, is characterized by a rather heterogeneous and complex strain pattern, which is highly scale dependent (Fig. 12). This pattern provides information about the roles of compositional and mechanical anisotropies in the deformation of mid-crustal basement rocks. The observed pattern is a result of a combination of pre-Alpine anisotropies, changes in the kinematic framework, strain localization processes, and shear zone evolution. In this light, variations in the large-scale

background strain in host rocks must be distinguished from highly localized strain in shear zones (Figs. 3, 12, 13).

## 5.1 Alpine kinematic evolution

In the literature, two end-member concepts for the structural evolution of the internal deformation of the Central Aar massif have been discussed: (i) The bulk coaxial shortening model, where structures evolve during a single major deformation event (Choukroune and Gapais, 1983; Gapais et al., 1987); and (ii) multiphase deformation where different events occur sequentially in time (Steck, 1968; Rolland et al., 2009; Table 2). Studies favoring (i) were conducted in the central to northern part of the study area only (CAGr-GrGr of Fig. 2), missing the important large-scale strike-slip structures that occur along the Grimsel Pass shear zone (GPSZ) in the south (Figs. 2, 8, supplementary material Fig. F). (ii) Along with this unintended omission, a number of data sources support an interpretation involving multiphase deformation, including cross-cutting relationships (Figs. 2, 7, 9 and supplemental material Figs. B-F), different radiometric ages (Challandes et al., 2008; Rolland et al., 2009; Wehrens 2015) and a change in kinematics (Steck, 1968; Rolland et al., 2009), which facilitate the recognition of the Handegg and Oberaar phase cross-cutting relations indicate a clearly younger relative age of the Oberaar strike-slip structures compared to Handegg reverse and normal faulting (Figs. 9, supplemental material Figs. B-F, Table 2). Recent radiometric dating on neocrystallized mica corroborate at least a two-step deformation: ~22-17 Ma (Challandes et al., 2008; Rolland et al., 2009) and 13.8-12.2 Ma (Rolland et al., 2009), which we correlate with the Handegg and Oberaar phase, respectively (see locations of

radiometric ages in Fig. 7). The change from biotite-stable metamorphic conditions ( $T > 400^{\circ}\text{C}$ ) of the Handegg structures to retrogressive mineralogical suites (e.g., chlorite and white mica stable, biotite unstable) of the Oberaar strike-slip shear zones also favor more than one deformation event. Last but not least, deformation further localized under cooler deformation conditions, forming the large-scale dextral Grimsel Pass strike-slip fault zone with the hydrothermally active Grimsel Breccia Zone in its core (Belgrano et al., 2016).

Collectively, these facts favor a multi-event deformation history, which is the tectonic scenario that we adopt for our analysis (Fig. 12). The gradually increasing metamorphic grade southward in the Haslital results from reverse shearing along the steeply S-dipping Handegg-phase shear zones. In general, these shear zones uplifted the southern hangingwall block exhuming rocks of higher metamorphic rocks (Fig. 12b). The accumulations of these south block up movements result in the nowadays exposed increasing in metamorphic grade from north to south.

The occurrence of reverse and normal faulting, respectively, along the major faults and the secondary branches (Figs. 13, supplementary material Figs. B,C,F) indicates the existence of a conjugate set, with preferential South block up movements as inferred by the dominance of reverse faults. Despite this clear geometric relationship in key outcrops, it might therefor be confusing to find similar shear plane orientations with normal and reverse shear senses (e.g. Fig. 8 see GrGr). Two different effects may cause this apparent discrepancy: (i) Progressive change in the major shear-zone orientation from steeply south dipping towards steeply north dipping from N to S (cf. Fig. 8 GrGr to AAZ). In the latter case, also the secondary branches will change their orientation yielding in



aforementioned overlap in shear plane orientations with opposing senses of shear. (ii)  
Passive rotation of the conjugate set of shear zones and reduction in the acute angle  
between them owing to horizontal shortening during Alpine compression.

(INSERT FIGURE 13 HERE)

The onset of the Oberaar phase had a clear change in kinematics, involving  
increased strain localization with greater strain partitioning. These changes might either  
have occurred abruptly or gradually. We observe rotations of the originally steeply south-  
plunging lineation, through a moderately E plunge, into a slightly E plunging to  
subhorizontal orientation (Figs. 2b, 7). This geometry is nicely reflected in the case of the  
strike-slip shear zone at Oberaarsee (Figs. 2, 10 and sz10 in Fig. 7b as well as in  
supplementary material Figs. B(b), F), where the rotation of the lineation is documented  
from the older high temperature parts preserved in the rim of the shear zones (lineations  
plunge from 69-58°) towards the young low temperature center of the shear zones  
(lineations plunging between 32-13° towards the ENE).

Despite some apparently contradicting cross-cutting relationships stated above, we  
suggest that the three orientations of the Oberaar-phase shear zones (SZ<sub>Oa</sub>, SZ<sub>Ob</sub>, SZ<sub>Oc</sub>)  
were simultaneously active within the same kinematic framework: First, the km-scale  
shear zones show no cross-cutting relationship. Instead Oberaar<sub>b</sub> shear zones rotate into  
Oberaar<sub>a</sub> ones (Fig. 7b, Sz9 and Sz10). Second, they all formed mylonites with the same  
stable mineral assemblage, pointing to similar metamorphic conditions during ductile  
shearing. Third, they all show strong strike-slip/oblique-slip components, which contrast  
the Handegg structures and are typical for the Oberaar phase related shear zones (Figs. 2,  
7, see also Steck, 1968; Rolland et al., 2009). The dextral ENE-WSW striking major

strike-slip shear planes show similar orientations as shear zones from the Handegg phase (Fig. 13). Based on these observations, we suggest a formation of the three Oberaar orientations within the same kinematic framework, and interpret the dextral E-W to ENE-WSW shear zones and the sinistral NE-SW shear zones, respectively, to represent anti- and synthetic Riedel shear orientations (Fig. 13b). Hence the different strike-slip orientations belong to the same kinematic regime and can be attributed to an overall dextral transpressional framework (see also model of Carreras et al., 2010) with simultaneous activity. The apparently contradicting cross-cutting relationships at the outcrop-scale might therefore reflect local relative incremental activities of individual decameter-scale Oberaar<sub>0</sub> shear zones during the overall transpressive movements. In fact, the formation, slight rotation and deactivation of local shear zones is typical for non-coaxial shearing of Riedel systems.

## 5.2 Effect of pre-Alpine anisotropies on Alpine deformation

Generally, a considerable number of pre-Alpine material anisotropies served as nucleation sites for Alpine deformation. They include: i) compositional variations in the meta-magmatic rocks; ii) lithological contacts; and iii) pre-Alpine deformation fabrics (Fig. 12a).

- i) Most important are original compositional variations in former magmatic rocks (Figs. 3, 12). Particularly variations in the amount of potential ‘mechanically weak’ phases, such as quartz and mica (e.g., Vernon and Flood, 1988) combine with the dimension of the corresponding magmatic body to directly affect the degree and scale of Alpine deformational overprint (Fig. 12). Deformation in the large-scale plutons has to be distinguished from that

in the smaller magmatic dikes (aplites, metamafic dikes). The volumetrically prominent CAGr and SWAGr with their weakly schistose fabrics, contain a modest general background strain compared to the moderately schistose and more mafic GrGr (Figs. 3, 12b, Table 1). Since the peak-Alpine metamorphic grade is nearly identical within all three intrusive rock types (450°C), it is the only slightly enhanced mica content of the GrGr (10-15 vol%), compared to that of CAGr/SWAGr (4-8 vol%), which forces the latter to behave more rigidly and allows concentration of deformation in the GrGr (Figs. 3, 12b). Note that this compositional variation also seems to affect the nucleation of shear zones either via ductile shearing (GrGr) or brittle fracturing (CAGr/SWAGr, see Wehrens et al. in press).

A similar compositional effect related to the sheet-silicate-content also accounts for the opposing deformation behavior of mafic and aplitic dikes (Figs. 3g,h; 12b, supplementary material Fig. E). Associated with the largest mica content in the study area (mica > 50 vol%), meta-mafic dykes generally have a strong internal foliation and invariably acted as Alpine ductile shear zones, when suitably oriented for shearing (Fig. 3g,h, supplementary material Fig. E(b)). If unfavorably oriented, host-rock-related shear zones crosscut the dykes (supplementary material Fig. E(a)), generating a new internal foliation for the dyke, which is parallel to the shear plane (e.g., SZ 7, Fig. 7b). On the other hand, aplitic dykes have the smallest mica contents (< 2 vol%) and developed biotite coated fracture networks when suitably oriented for shearing, but have almost no internal foliation (Fig. 3g). Instead, deformation

is always localized within the host rock adjacent to the aplite contact (SZ8, Figs. 7b and 9e,f). Similar observations have been made from the Tauern window (Pennacchioni and Mancktelow, 2007).

- ii) Large-scale high-strain zones, whose thicknesses range from one meter to several tens of meters, occur along lithological boundaries between post-Variscan intrusives and pre-Variscan basement. These zones are the boundaries between the GrGr and Grimsel Zone (e.g. SZ10, Fig. b) and between the Grimsel Zone and Southwestern Aar granite (e.g. SZ12, Fig. b).
- iii) Within the pre-Variscan basement of the Grimsel Zone, an axial planar foliation can occasionally be found that is cut by aplitic bodies related to the granite intrusion. Therefore, this foliation has a pre-Variscan origin (SZ10, 9). The remnants of pre-Alpine folds with axial plane foliation in the shear zones of the Grimsel Zone might also be an indicator of a long lasting deformation (Bell, 1978; Alsop and Holdsworth, 2002; Carreras et al., 2010), involving a possible pre-Alpine shear component. Note that this pre-existing planar fabric was reactivated during both the Alpine Handegg and Oberaar phases of deformation.

### 5.3 Alpine strain localization

#### 5.3.1 Initial Alpine strain localization

Two end-member nucleation sites for strain localization are recognized in the study (Fig. 12): (i) nucleation along pre-existing mechanical anisotropies (Figs. 4, 12) and (ii) formation of new anisotropies by brittle failure (Figs. 5, 12b,c). (i) In terms of

initiation of Alpine shear zones, many important structures that have large thickness and lateral continuity result from reactivation of pre-existing mechanical anisotropies, or structural discontinuities that either evolved out of a lithological contact (e.g. GrGr - Grimsel Zone contact, Figs. 6, 7, 12a), compositional heterogeneity, or an earlier deformation event (Fig. 10). The sheared domains within the Grimsel Zone, for example, have a protracted long-lasting multistage reactivation history. Here, a (pre-) Variscan structure served as a km-scale mid-crustal mechanical anisotropy already present during emplacement of post-Variscan intrusions. Particularly, the intrusion and crystallization of the aplitic boundary facies and the Southwestern Aar granite generated isotropic host rocks with very small sheet-silicate content. Consequently, a considerable contrast in effective viscosity evolved between these mechanically stiffer plutonic rocks and the weaker, sheet-silicate-rich gneisses of the Grimsel Zone. Similar contrasts within the post-Variscan intrusives (i.e., meta-mafic dykes, aplitic dykes) induced localization of ductile strain as long as their orientations were appropriate for reactivation within the regional kinematic framework (Fig. 12a, 13). Especially around the Rättrichsbodensee, the pronounced occurrence of meta-mafic dykes at the transition from CAGr to GrGr caused strain to localize along these mechanically weaker magmatic precursors. Deformation reactivated such contacts during the Alpine orogeny.

In general, the sheet-silicate content and spatial distribution of sheet-silicate-rich rocks was crucial for controlling the intensity distribution of Alpine deformation in high strain domains, as well as for the background strain in weakly deformed domains of much of the host rocks (Fig. 12a). Sheet-silicate-rich lithologies like the Grimsel Zone, GrGr and meta-mafic dykes have a strong internal ductile deformation characterized by a

greater density and thickness of Handegg phase high-strain domains, compared to the more isotropic granitic rocks with a smaller sheet-silicate content (Figs. 6, 7 and 12). Besides the changes in high strain shearing, the higher sheet-silicate content in the GrGr also resulted in a larger amount of background strain in the GrGr, compared to the CAGr. This influence is illustrated by the higher proportion of strongly schistose fabrics within the GrGr (Figs. 3, 12b,c).

(ii) In contrast to type (i) shear zones within the isotropic parts of the post-Variscan plutons, shear zones with small sheet-silicate content are very discrete and thin (<0.1 m). They are occasionally several km in length, dissecting the granitic bodies in a regular planar manner. Given their large length to thickness ratio, combined with their straight planar geometries, we infer that these shear zones must have nucleated on pre-existing brittle fractures under semi brittle-ductile conditions. Additional evidence for brittle deformation at elevated temperature in this ductile deformation regime is found in biotite-bearing fracture coatings and epidote veins, which are overprinted by biotite- and white mica-bearing ductile shear zones (see also Wehrens et al., in press). Figure 5a-c documents such an overprinting sequence, comprising an initially formed network of biotite-coated fractures, which was overprinted by an ultramylonite. Such ultramylonites often widen and terminate in brittle horse-tail structures (Fig. 5c), providing further evidence for brittle structures acting as precursors for ductile shearing in the case of the CAGr (see also Wehrens 2015).

The idea of brittle precursors for the nucleation of granitic shear zones deformed under greenschist or amphibolite facies metamorphic conditions has been suggested by several authors (Segall and Simpson, 1986; Mancktelow and Pennacchioni, 2005; Füsseis

et al., 2006; Handy et al., 2007; Pennacchioni and Mancktelow, 2007; Füsseis and Handy, 2008). In the case of our mid-crustal rock suite of granitoid origin, we infer that the fracture-induced nucleation of ductile shear zones is of particular importance in the isotropic sheet-silicate poor plutonic bodies already active during the Handegg phase (Figs. 12b and 13). With progressive shortening, they were probably steepened and reactivated as Oberaar<sub>a</sub> strike-slip shear zones. In contrast, Oberaar<sub>b,c</sub> orientations with their opposing shear senses, represent a simultaneously active conjugate set, which was newly formed during Oberaar<sub>a</sub> shearing. Despite their clear ductile deformation style, the similarity in geometry and kinematics to syn- and antithetic Riedel shear zones is appealing, provoking us to also postulate a brittle origin for the ductile Oberaar<sub>b</sub> phase and Oberaar<sub>c</sub> phase shear zones (Fig. 13b). Similar correlations between brittle and ductile features in shear band formation have previously been proposed (Shimamoto, 1989). Note that all three Oberaar phase shear-zone orientations were reactivated during retrograde deformation as brittle faults representing important pathways for the circulation of hydrothermal fluids (Belgrano et al., 2016).

### *5.3.2 Evolution of strain gradients*

Following from the two types of nucleation sites for ductile shearing (sheet-silicate content and fracture-induced mechanical anisotropy), the evolution of strain gradients has to be considered.

- i) During ongoing deformation of ductile shear zones (i.e., sheet-silicate-rich zones), grain-size reduction induces strain localization (Fig. 12b,c). Meter-wide strain gradients formed from a weakly to moderately deformed rim towards a mylonitic

central zone and an ultramylonitic shear zone core. Hence, typical shear zone narrowing occurs (e.g., Means, 1995; Ebert et al., 2007; Herwegh et al., 2008; Haertel and Herwegh, 2014, Herwegh et al., 2016). Monomineralic quartz domains in the shear zone center are deformed by dislocation-creep processes, as they have strong crystallographic preferred orientation (CPO) correlated with textures related to subgrain rotation recrystallization in the fine-grained domains. The even smaller, 5 to 50  $\mu\text{m}$ , recrystallized grain size combined with the equiaxed grain shapes and the absence of CPO within polymineralic domains suggest viscous granular flow as the dominant deformation mechanism (e.g., Stünitz and Fitz Gerald, 1993; Paterson, 1995; Herwegh et al., 2011).

- ii) In contrast, shear zones, which nucleated along fractures and are characterized by discrete narrow, high strain zones, must have widened after initial fracturing (Fig. 12b,c). Fracturing at the grain scale results in a grain size decrease, dilatancy and an increase in reactive surface area. These preconditions promote fluid infiltration, mass transfer processes and mineral reactions. As a consequence, new sheet silicates crystallize and the proportion of these mechanically weak phases increases in the shear zones.

In this way, the effective viscosity of type (ii) shear zones converges toward that of type (i) shear zones by a reaction-weakening process (Fig. 12c). Nevertheless, major differences exist in the thicknesses of the two contrasting types of strain localization. Besides finite strain, in (i), the dimensions of the original compositional heterogeneities substantially influences the thickness of the high strain zones, while in (ii), the reaction progress and amount of fluid are the controlling parameters (see Wehrens et al., in press).



During retrograde deformation, shear zones further narrowed within sheet-silicate-rich domains (Figs. 11h and 12c). The local evolution of sheet-silicate-rich domains is most likely a combined effect of producing white mica and chlorite during ongoing cooling and synkinematic infiltration of fluids and precipitation of white mica. With progressive cooling, brittle deformation increases, finally leading to the formation of cataclastic zones and brittle fault gouges (Fig. 5d,e). Note that these gouges are not preserved at surface outcrops, but can be frequently found in drill cores from the underground tunnels (Wehrens et al., in press). Here, they mostly evolved out of ductile shear zones suggesting continuous strain localization with progressive cooling. Sheet-silicate-rich shear zones may develop under varying metamorphic conditions as indicated by previously published examples of shear zones with locally different compositions (Oliot et al., 2010; Goncalves et al., 2012).

(INSERT FIGURE 12 HERE)

### 5.3.3 *Meso-scale deformation*

On the small scale, individual shear zones are described in terms of their localization history, from initiation to final expression. On a larger scale, a mid-crustal section of several km is characterized by a particular distribution of such shear zones. Surface mapping (Fig. ) as well as subsurface quantification of deformation along the “Transitgas-tunnel” (Fig. 6) allowed for determination of the most important factors contributing to the km-scale strain distribution. This mid-crustal section is characterized by a multitude of shear zones ranging from mm to meters thickness (90-125 shear zones per km). Similar dimensions of shear-zone thicknesses and shear-zone spacings were

found in the Mont Blanc Massif (Rossi et al., 2005; Rolland et al., 2008). In the Aar massif, the strain distribution indicates an increase of deformation towards lithological contacts (Fig. 6a). Furthermore, a relationship between the deformation intensity and compositional variations is indicated, whereby a greater sheet-silicate content results in an increase in the thickness of the deformation-induced structures, the density of the structures and the volume percentage that both localized and distributed deformation occupies (Fig. 6b,c and Table1). This correlation is less obvious for the aplitic boundary facies as well as the Southwestern Aar granite. There is a large amount of pervasive deformation within these relatively poor sheet-silicate-content rocks. This discrepancy may arise from boundary effects due to the limited length of the transect studies (several hundred meters; Fig. 6a). A relatively large part of the transect length is occupied by intensely deformed lithological contacts. Furthermore, both the aplitic boundary facies and the Southwestern Aar granite are located close to the very highly strained Grimsel Zone that may shield them from more intense deformation by being more efficient as it is weaker for deformation.

Generally these observations illustrate that, although on the meter scale, localization occurs, on the scale of several km, deformation may be described by homogeneous strain distribution over a multitude of shear zones. Smaller structures dominate in the sheet-silicate-poor areas, compared to meter-scale shear zones in the sheet-silicate-rich zones. At least in the case of our mid-crustal section, deformation is never localized along only one major shear zone, but is always distributed.

## 5.4 Geodynamic implications

Based on deformation overprinting relations in the Mesozoic sediments of the autochthonous cover of the Aar massif and the Helvetic nappes, a kinematic model for their evolution has already been postulated (Burkhard 1988; Herwegh and Pfiffner 2005). Based on our new results, we can refine this sequence because our data and conceptual framework for the shear zone pattern, and its kinematics and evolution through time, both provide new information for Alpine deformation on a regional scale and have important geodynamic implications.

Kinematic analysis of the Handegg phase and its associated orientations of the structures give first hints for a NW-SE related shortening associated with strong reverse faulting (Fig. , 13a,c). The activity of the associated shear zones has been dated at 22-17 Ma (Challandes et al., 2008; Rolland et al., 2009). This time interval correlates with the two deformation stages described by Burkhard (1988). The first stage, (Kiental phase of Burkhard, 1988), is defined by NW-directed thrusting and large-scale recumbent folding in the Doldenhorn nappe at around 30-20 Ma. In the subsequent Grindelwald phase, both the entire Helvetic nappe stack and the basement rocks of the Aar massif are updomed at 20 to 5 Ma (Burkhard, 1988).

The present day steep orientation (Fig. 2b) of the Handegg phase shear zones is unfavorably oriented for thrusting, however, their present day orientation may not match their orientation during shear, but even allowing for that possibility, they were likely steeply dipping requires other conditions to be active structures. Such high-formation angles may result from low differential stresses and/or high pore-fluid pressures (e.g.,

Sibson et al., 1988). The evolution of the Handegg structures might therefore be attributed to later stage shortening of the Kiental phase.

Ongoing NW-SE compression of the over-thickened crust and the steepening of Handegg phase shear planes resulted in lateral orogen-parallel extension, accommodated first by a gradual transition from Handegg to Oberaar phase oblique shearing component (strong vertical component), and then by Oberaar strike-slip shearing under greenschist facies metamorphic conditions ( $> 400^{\circ}\text{C}$ ). Therefore, a transpressional kinematic regime locally evolved during the Oberaar deformation phase.

At the larger scale, orogen-parallel dextral movement occurred simultaneously with the Oberaar phase along the Rhône Valley (Campani et al., 2010) and the Chamonix valley between the external Aiguilles Rouges massif and more internal Mont Blanc massif (Egli and Mancktelow, 2013). These structures are in part linked with the Simplon-fault system (Hubbard and Mancktelow, 1992). Consequently, en-echelon arranged strike-slip lateral ramps at the northern extent of the Rhone-Simplon Line can be correlated with the Oberaar phase of dextral shearing, which has been previously implied by other studies (Rolland et al., 2009).

## 6 Conclusions

Alpine age mid-crustal deformation reported in this study was strongly controlled by a combination of reactivation of pre-existing mechanical anisotropies and variations in the effective viscosity of the host rocks. Pre-Alpine anisotropies included a pre-Alpine foliation in the (pre-) Variscan basement in the Grimsel Zone, compositional variations in sheet-silicate content of magmatic host rocks as well as their lithological contacts. These

pre-existing heterogeneities were used during both the Alpine Handegg and Oberaar deformation phases, where strain partitioned between volumetrically important background strain and deformationally important, highly localized strain in shear zones. Interestingly, the quartz-rich rocks, i.e. felsic magmatic host-rocks (CAGr, SWAGr, aplites), represent the mechanically more rigid bodies in this mid-crustal section, although conditions of ductile deformation of quartz were reached. Instead, bulk deformation was focussed in the more mafic rocks (GrGr, metabasic dikes) due to their abundant sheet-silicate contents. Consequently, the spatial distribution of these mafic rocks controlled to some extent the concentration of shear zones in these mafic domains (Fig. 12b). In terms of localized deformation in wide ( $> 1$  m shear zone thickness) high strain zones, they occur commonly along lithological/compositional contacts, probably owing to stress concentrations. Nonetheless the multitude of thin ( $< 0.2$  m wide) but several 100-m-to-kilometers-long shear zones, dissecting the entire width of pre-existing granitoids, created a very well developed strain localization pattern. In the homogeneous plutonic host rocks (CAGr, SWAGr), several lines of evidence point toward shear-zone nucleation along brittle fractures followed by ductile deformation during shearing (Figs. 5, 12c). Here, strain weakening due to mechanical grain-size reduction and reactions via chemical mass-transfer processes result in sheet-silicate-enriched, fine-grained polymineralic ultramylonites, facilitating ductile deformation along the high-strain zones (Stünitz and Fitzgerald, 1993; Füsseis and Handy, 2008). In this way, two different deformation histories, one brittley-based and the other ductiley-based, led to the same outcome of deformation localized in shear zones as a function of the initial material properties of the host.

Kinematically, a change from a contractional to a local transpressional setting is observed where:

The Handegg phase is marked by shortening in combination with dominant south-block-up shearing under greenschist facies conditions, resulting in crustal thickening.

Shear zones range from mm- to m-scale, and are the dominant type of shear zone throughout the area.

The Oberaar phase is characterized by transpression and dextral strike-slip deformation, still under greenschist facies conditions. In the Grimsel Zone, these shear zones form a large dextral domain, whereas in the post-Variscan intrusives they are narrower and more discrete. Retrograde deformation affected some of the Oberaar phase shear zones.

In conclusion, the classical “anastomosing” deformation pattern of the Grimsel shear zones is not the result of a single deformation event. Rather the deformation pattern progressively evolved during a complex and long-lived deformation history that combined a changing kinematic framework, with variable sheet-silicate contents in different units controlling shear-zone initiation along a variety of pre-Alpine geometrical anisotropies. In this sense, initial mid-crustal heterogeneity has a major effect on the control of mid-crustal deformation in the Aar massif up to the present day.

## **Acknowledgements**

We would like to thank the following people and institutions for their support in our project: KWO, NAGRA, Raphael Schneeberger, Samuel Mock, Guido Schreurs, Max Peters, Armin Dielfolder, Tom Belgrano and Daniel Egli. The article greatly benefitted

from the thorough reviews of D. Czeck and R. Law as well as the excellent editorial handling by W. Dunne. Financial support by SNF (project 200021 132196) is greatly acknowledged.

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## Figure captions

Fig. 1: Overview map of the Aar massif with the Haslital transect from Meiringen to Grimsel Pass (modified from Goncalves et al., 2012). Main map is an inset of the map of Switzerland on the upper left and small inset in the map shows study area (Fig. 2). Swiss coordinates are given in km.

Fig. 2: (a) Geological map of the Haslital area [based on Stalder (1964), Steck (1968), Abrecht (1994) and our own observations] containing a pervasive pattern of ductile shear zones. Major and minor shear zones are represented by thick and thin lines, respectively. (b) Lower-hemisphere equal-area projections of both poles to the shear planes and the stretching lineations for the five analysed units investigated in this study. Shear senses are color-coded by the symbols.

Fig. 3: Weakly deformed host rock (left column) with corresponding strongly deformed tectonite (central column). Right column indicates both sheet silicate content (light grey) and strain intensity variation in background (blue gradient) and high strain zones (red gradient). Note, the greater the sheet silicate content the greater the strain intensity as manifested by an increase in foliation intensity and grain-size reduction. CAGr: Central Aar granite; GrGr: Grimsel granodiorite; SWAGr: Southwestern Aar granite. Grimsel Zone belongs to pre-Variscan basement, where  $S_{\text{prealp}}$  shows a folded pre-Alpine foliation. Magmatic dikes are situated in CAGr. Table 1 contains data about detailed mineral contents.

Fig. 4: Strain gradients in the granodiorite. Foliation intensity varies from weak (left) to moderate (right) owing to the increased biotite content of the granodiorite. (b) Mylonitic granodiorite. (c) Transition from mylonitic (right) to ultramylonitic (left) granodiorite.

Fig. 5: Evidence for brittle deformation in the granitoid rocks. (a-c) Ultramylonitic shear zone in weakly deformed Central Aar Granite (CAGr). (a) Overview image showing an ultramylonitic shear zone adjacent to networks of sub-parallel biotite(bt)-coated fractures. (b) Enlarged view documents that the fracture network is cut and overprinted by the ultramylonite. (c) The ultramylonite widens at its end into a horse tail structure consisting of brittle biotite-coated fractures. (d) Mylonitic shear zone in a strongly foliated Grimsel granodiorite (GrGr) cut by a retrograde brittle cataclastic zone. (e) Weakly foliated GrGr from the nagra (National Cooperative for the Disposal of Radioactive Waste) Grimsel Test Site overprinted by a hydrothermally altered cataclasite. Size of pen used for scale approx. 15 cm.

Fig. 6: Data gathered from the Transitgas tunnel (Schneider, 1974) to quantify strain distribution. a) Frequency histogram of the abundance of all mylonitic and cataclastic zones as a function of position along the tunnel transect. Profile positions of lithological units are indicated. b) Summary of number of deformation structures per km according to their thicknesses for each lithological unit. Red shading connects large-scale shear zones with thicknesses  $>0.5$  m c) Percentage of rock volume for each unit affected by a specific deformation structure. CAGr: Central Aar granite; GrGr: Grimsel

1074 granodiorite; ABF: aplitic boundary facies, GSZ: Grimsel Zone, SWAGr:  
1075 Southwestern Aar granite.

1076 Fig. 7: Shear zone maps of the study area between Rättrichsbodensee (R) and  
1077 Gletsch. a) Handegg phase shear zones. Note the increase in density and  
1078 thickness of the shear zones from the Central Aar granite to Grimsel  
1079 granodiorite. White arrows indicate Handegg phase shear zones cut by the  
1080 large-scale Grimsel Pass Shear zone (GPSZ). (b) Oberaar phase (a), (b) and  
1081 (c) shear zones. Note the set of thick dextral shear-zones at Oberaarsee (see  
1082 Figure 2a for locations) presenting the GPSZ. Radiometric ages are from  
1083 Challandes et al. (2008, with asterisk) and Rolland et al. (2009). Capital  
1084 letters B-F show locations of supplementary Figures B-F also documenting  
1085 cross-cutting relationships.

1086 Fig. 8: Lower-hemisphere equal-area plots showing the orientations of the shear  
1087 planes (great circles) and related stretching lineations for the Handegg phase  
1088 (left column) and Oberaar phase (right column) structures in the different  
1089 lithological units (CAGr: Central Aar granite, GrGr: Grimsel granodiorite,  
1090 GSZ: Grimsel Zone, SWAGR: Southwestern Aar granite, AAZ: Ausserberg  
1091 –Avat Zone.). Handegg phase: empty squares and filled red circles indicate  
1092 stretching lineations of normal (stippled great circles) and reverse (solid  
1093 great circles) shear zones. Red domain represents manually drawn envelope  
1094 of the majority of the shear planes. Oberaar phase: filled blue (dextral)  
1095 circles and empty blue (sinistral) squares show stretching lineations of  
1096 Oberaar<sub>a</sub> shear zone orientations; filled blue (dextral) rhombs and empty

1097 blue (sinistral) rhombs show stretching lineations of Oberaar<sub>b</sub> shear zone  
1098 orientations; black filled circles (dextral) and empty squares (sinistral)  
1099 represent stretching lineations of Oberaar<sub>c</sub> shear zone orientations. Dark and  
1100 bright blue shading present manually drawn envelopes of the majority of the  
1101 dextral (solid great circles; Oberaar<sub>a</sub> and Oberaar<sub>b</sub> orientations) and sinistral  
1102 (Oberaar<sub>c</sub> orientations) (stippled great circles) shear planes, respectively.

1103  
1104 Fig. 9: Field examples showing crosscutting of older Handegg structures by  
1105 younger Oberaar shear zones (left column: field photographs, right column:  
1106 schematic drawings). All images are in map view. Shear senses and  
1107 orientation of lineations are indicated. (a,b) Southwestern Central Aar  
1108 granite (SCAGr) outcrop with an old Handegg phase related foliation (S<sub>H</sub>)  
1109 which is cut (i) by a dextral shear zone in Oberaar<sub>a</sub> orientation (SZ<sub>Oa</sub>), (ii) A  
1110 sinistral shear zone in Oberaar<sub>c</sub> orientation (SZ<sub>Oc</sub>) and (iii) shear bands in  
1111 Oberaar<sub>b</sub> orientations (S<sub>Ob</sub>). (c,d) Grimsel granodiorite outcrop showing a  
1112 dextral Oberaar<sub>a</sub> phase shear zone (SZ<sub>Oa</sub>) with S-C fabric being cut by a  
1113 dextral Oberaar<sub>b</sub> phase (SZ<sub>Ob</sub>) shear zone. Note the moderately SE dipping  
1114 lineations indicating dextral oblique slip. (e,f) Grimsel granodiorite (GrGr)  
1115 outcrop where an Oberaar<sub>b</sub> phase shear zone (SZ<sub>Ob</sub>) runs along an aplitic  
1116 body and crosscuts a Handegg phase shear zone (SZ<sub>H</sub>). Note the steeply  
1117 South plunging and subhorizontal SE plunging stretching lineations of the  
1118 Handegg- and Oberaar-phase shear zones.

Fig. 10: Detailed map of the shear zone at the west end of Oberaarsee (see Figure 2a for location names). An old Handegg-Phase foliation in the Grimselgranodiorite (GrGr) is cut by a branch of the the large-scale Grimsel Pass shear zone (GSPZ). Lineations and shear sense indicators (e.g. C' structures, asymmetrically folded veins) document Oberaar Phase dextral strike slip to oblique slip.

Fig. 11: Field images (left column) and micrographs (right column) of magmatic Central Aar granite (CAGr) fabrics (a,b) as well as of Handegg- and Oberaar-phase shear zones (c-h). Appearance of isotropic CAGr at (a) the outcrop and (b) in thin section (from nagra Grimsel Test Site) with quartz (qtz), biotite (bt), chlorite (Chl) and k-feldspar (k-fsp). (c) Detail of mylonitic Handegg-phase shear zone (667231/162323) in Central Aar granite (subvertical section) showing in (d) an electron backscatter image of a polymineralic matrix (mainly biotite, quartz, feldspar) and dynamically recrystallized quartz bands. Note the smaller quartz and albite grain size (dashed box), being pinned by finely dispersed biotite in the polymineralic matrix, compared to the grain sizes in the monomineralic quartz band (qtz). (e) Oberaar<sub>a</sub>-phase shear zone in Grimsel Zone (668010/157059) with a C' structure indicating a dextral shear sense. (f) Thin-section showing a high temperature stage (Oberaar phase), where both white mica (wm) and biotite show stable coexistence in the same polymineralic microstructure during grain refinement by recrystallization (compare grain sizes with magmatic fabrics in b). (g) S-C fabric in SouthwesternAar granite (669630/157118)

indicating a dextral shear sense, where the C plane represents an Oberaar<sub>b</sub> phase shear zone. (h) Thin-section of an Oberaar<sub>b</sub> phase shear zone in SWAGr, recrystallized interconnected white mica bands parallel to C plane (entire section) dominate the ultramylonitic fabric demonstrating the lower temperature conditions. Diameters of pens are about 7-8 millimeters.

Fig. 12 A schematic overview of shear zone initiation and evolution. (a) Vertical N–S cross section representing pre-Alpine anisotropies and their differences in sheet-silicate content are illustrated from north to south, as well as a predefined fabric for the Grimsel Zone (GSZ). (b) The initial sheet-silicate content is a control of deformation distribution during the Handegg phase: (i) enhanced sheet-silicate contents result in wide ductile shear zones, (ii) brittle fractures present the precursors of subsequent ductile deformation in granitoids with low sheet-silicate content. c) With ongoing shearing initially brittle fractures are affected by a shear zone widening (iii) and broader ductile shear zones also develop here. Some of the shear zones are affected by a retrograde overprint and associated localization, first during late Handegg phase then during the Oberaar phase, forming first white mica domains and then cataclasites and fault gouges (iv).

Fig. 13: a, c) Lower-hemisphere equal-area plots and block diagram of Handegg phase shear zones, b,d) same presentation but for Oberaar phase shear zones. The large Oberaara phase dextral domain in the south of the study area is indicated as an analogue to the Grimsel Zone. Handegg phase shear zones are cross-cut by Oberaar phase zones (a) and (b). Within the large



1165 Obaraar<sub>a</sub> phase strain domains, C' structures developed with progressive  
1166 dextral strike-slip/oblique-slip shearing. Within the more homogenous rocks  
1167 to the north, a conjugate set with dominant synthetic and some antithetic  
1168 Riedel shears developed (Obaraar<sub>b</sub> and Obaraar<sub>c</sub> phase). The block diagram  
1169 shows the complex pattern of lensoid-shaped, weakly deformed domains  
1170 separated by high strain shear zones. Note that the block diagrams of (b,d)  
1171 are slightly rotated with respect to north for illustration purposes.

1172

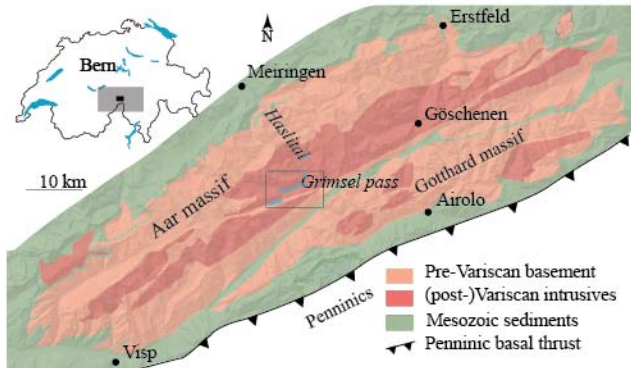
1173 Table 1, Composition of the lithological units. The most important minerals in  
1174 vol% are stated, as well as the data source. Note the distinct variation in  
1175 sheet silicate content. Data sources are: Stalder, 1964; Niggli, 1965; Keusen  
1176 et al., 1987; Schaltegger 1989. In Bt column green colour reflects high  
1177 biotite content. Red colour reflects low biotite content. Qtz = quartz, Kfs =  
1178 potassium feldspar, PL = plagioclase, Bt = biotite, Wm = white mica, Chl=  
1179 chlorite, Ep = epidote.

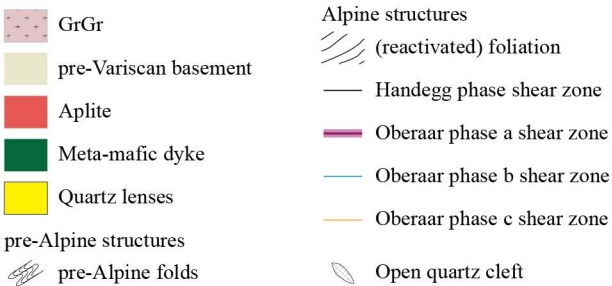
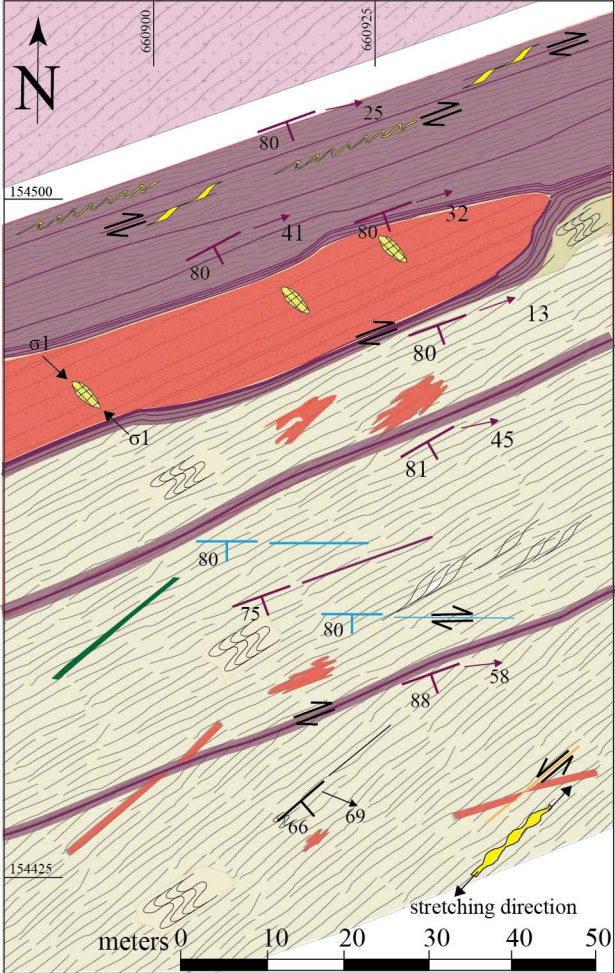
1180 Table 2, Correlation of deformation phases from this study to previous work. Note  
1181 that Stage 1 (Rolland et al., 2009) has a much larger variation in shear plane  
1182 orientation than the Handegg phase and Stage 3 is sinistral although  
1183 Obaraar<sub>b</sub> phase is dextral.

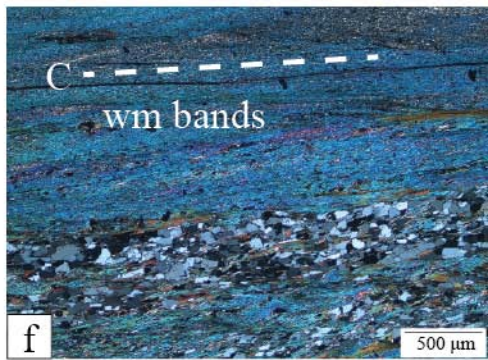
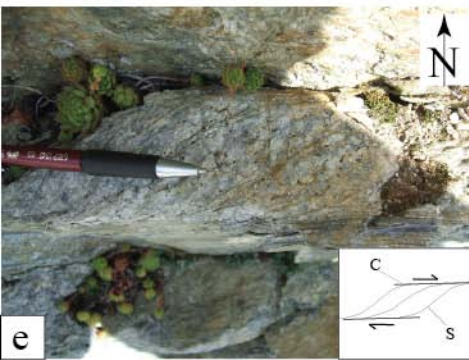
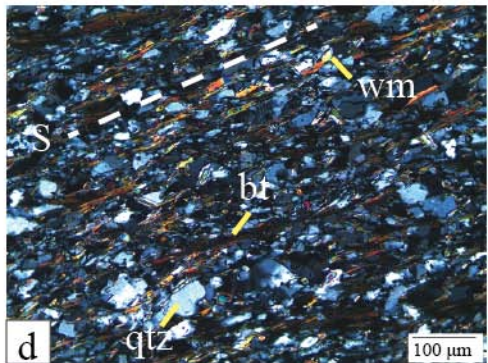
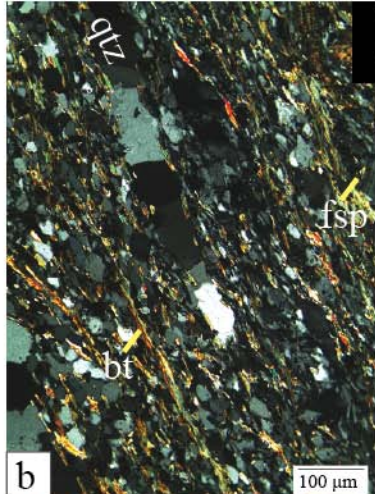
1184 Table 3, Description and characteristics of shear zones with large thickness. Shear  
1185 zone locations shown in Fig. 7.

1186 Table 4, Summary of microstructures in samples analyzed (X and Y are Swiss  
1187 coordinates. Deformation features observed in thin section include:  
1188 dominant quartz recrystallization (REX) mechanism within monomineralic  
1189 quartz aggregates (BLG - bulging, SGR - subgrain rotation). Compositional  
1190 information is the dominant mica, the associated mica with quartz  
1191 recrystallization, which mica occupies the strain shadows, minerals building  
1192 continuous bands. Assignment to deformation phase in most rightward  
1193 column. Note, although all phases have similar mineral stabilities, biotite-  
1194 rich (red) Handegg shear zones differ from white mica-rich (blue) Oberaar  
1195 shear zones. Additionally one chlorite shear zone (green) is present.

1196

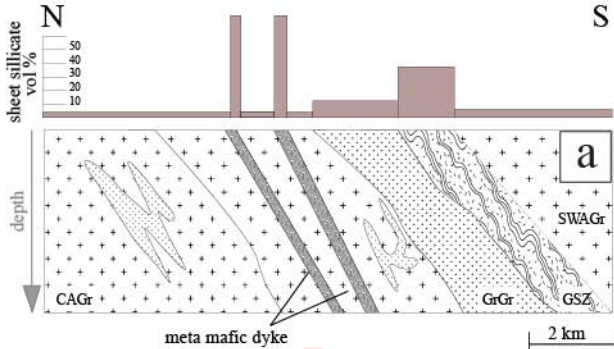




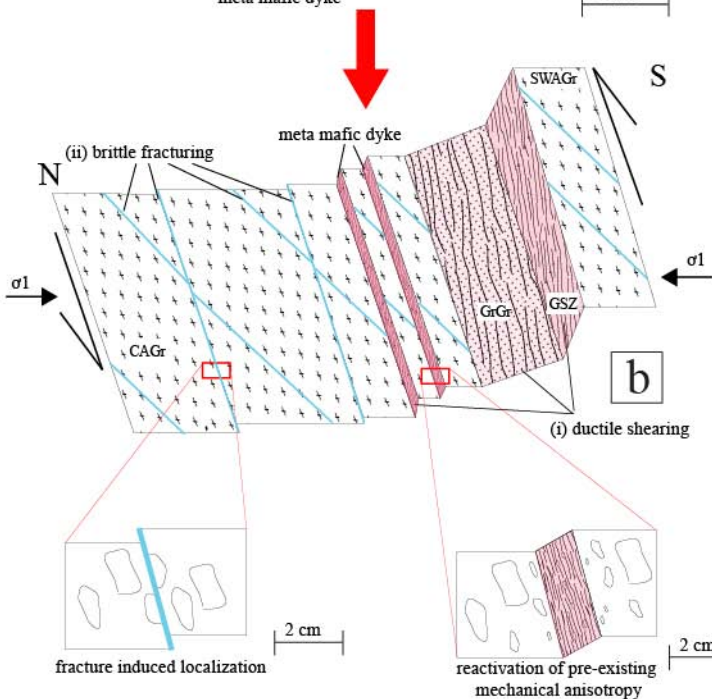




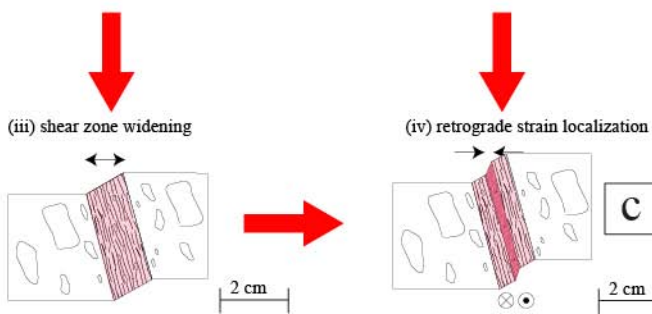
# pre-Alpine anisotropies

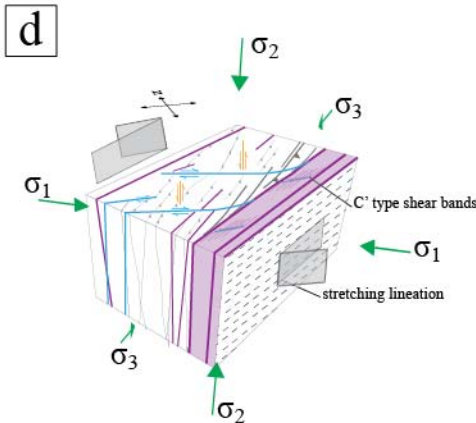
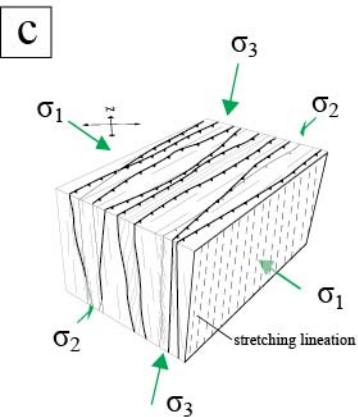
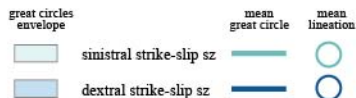
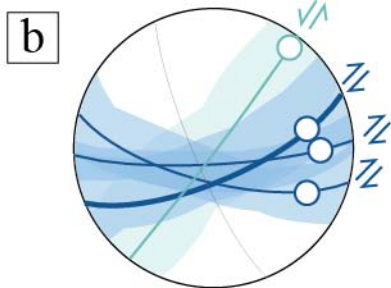
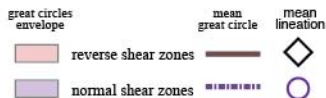
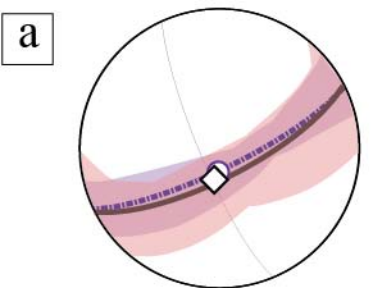


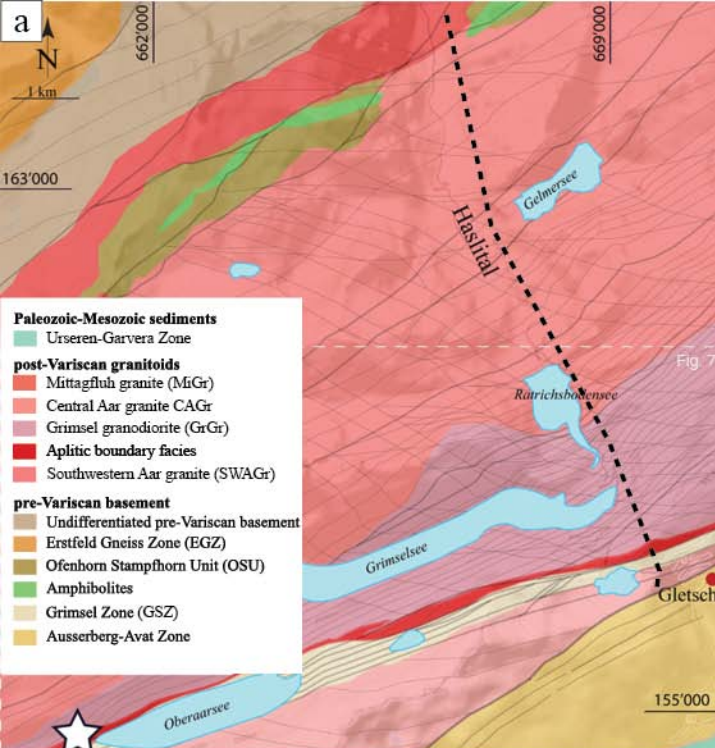
# initiation of Alpine shear zones



# evolution of Alpine shear zone

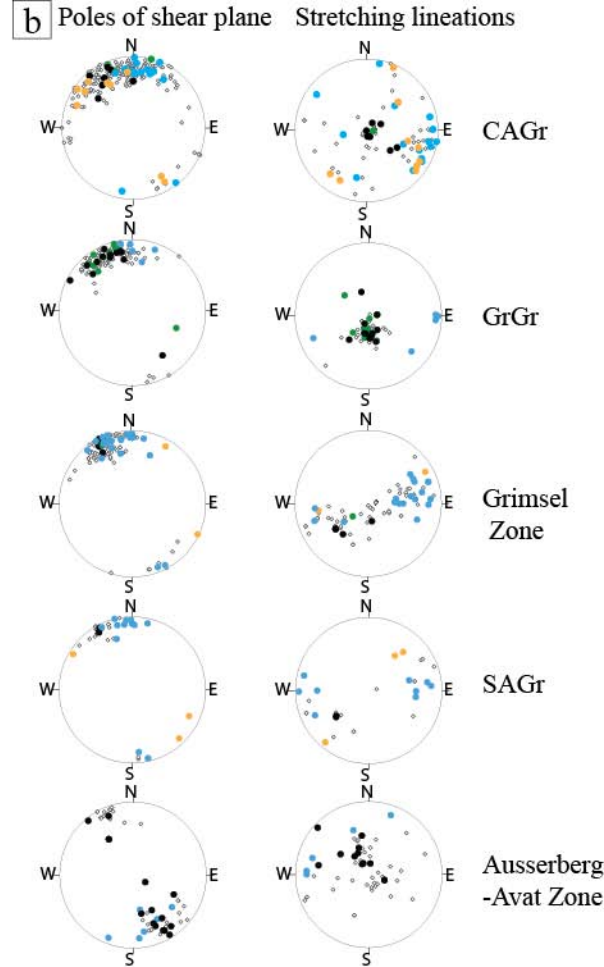




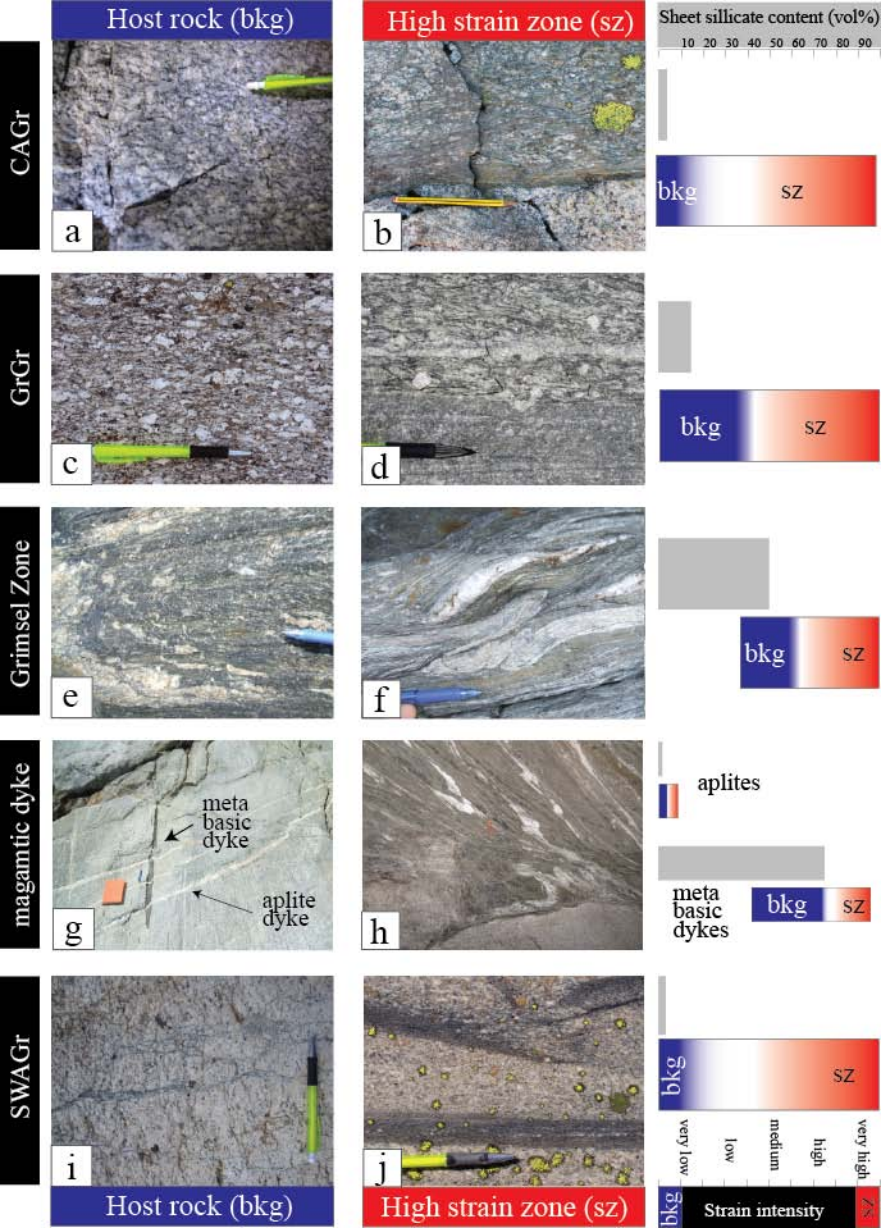


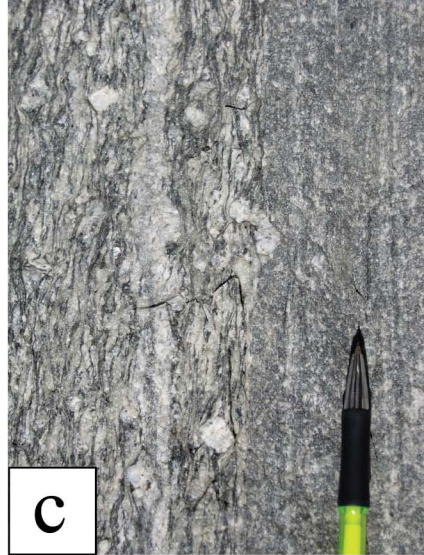
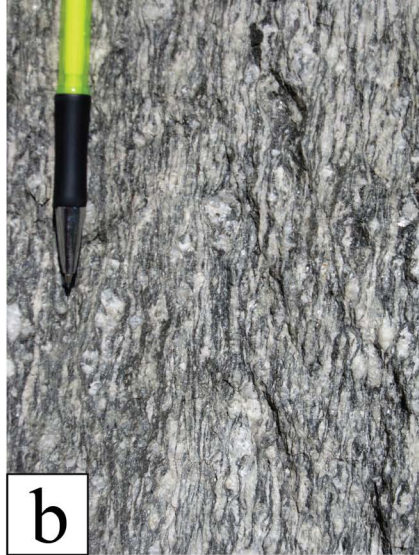
- shear zone
- major shear zone
- ☆ Obaar mapping (Fig. 10)
- approximate trace of the Transitgas tunnel

- unknown shear sense
- reverse shear sense
- normal shear sense
- dextral shear sense
- sinistral shear sense

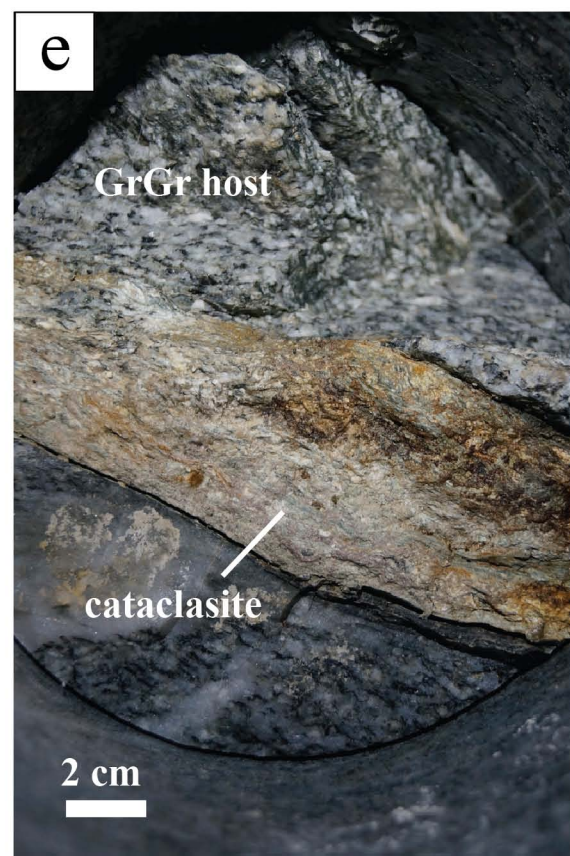
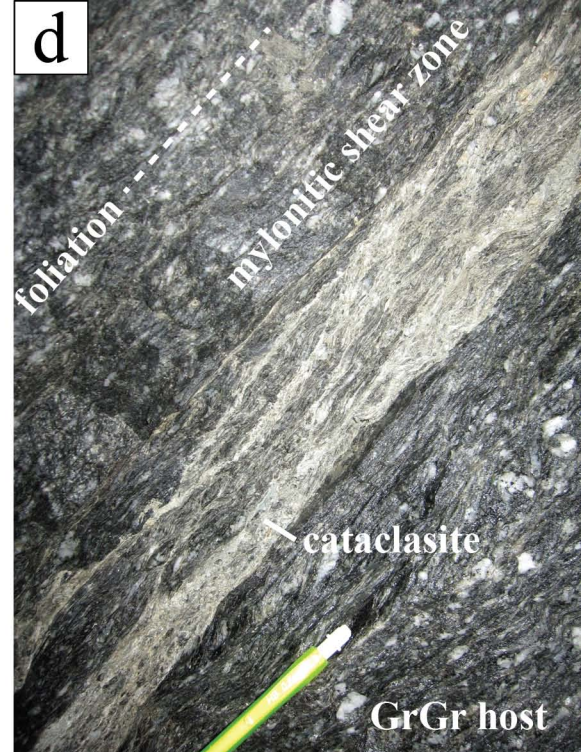
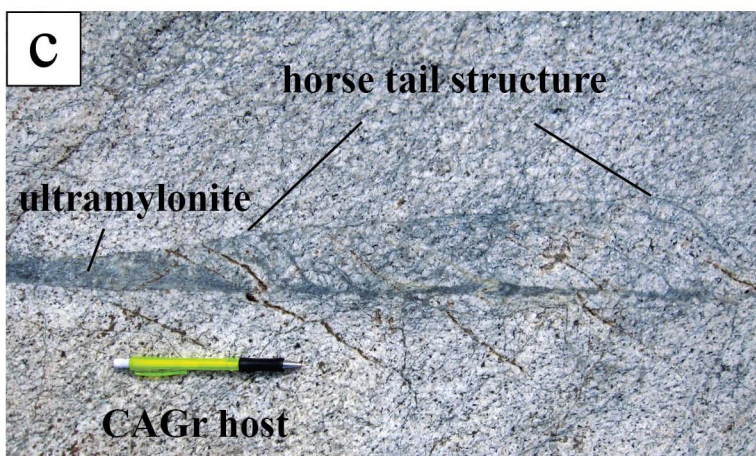
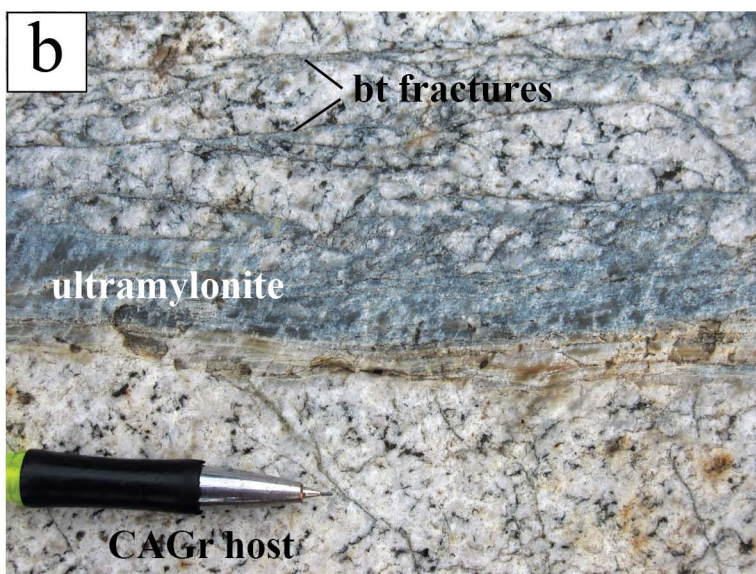
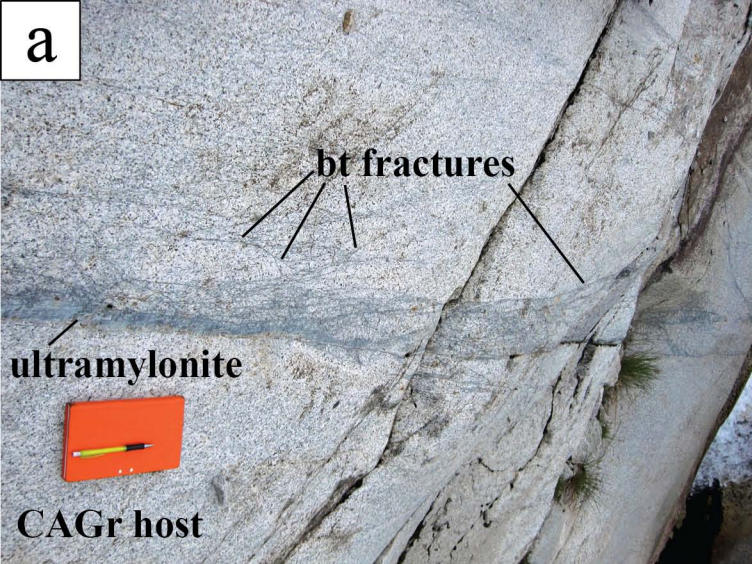




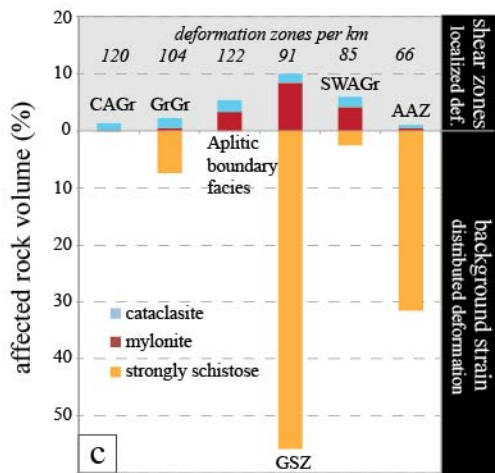
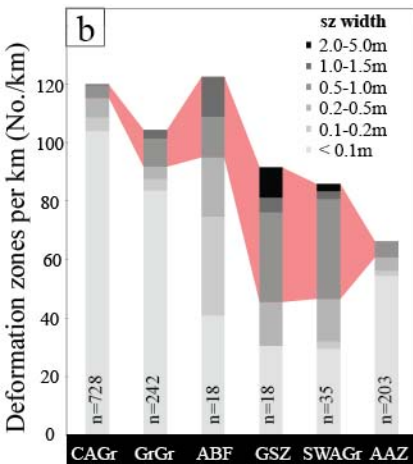
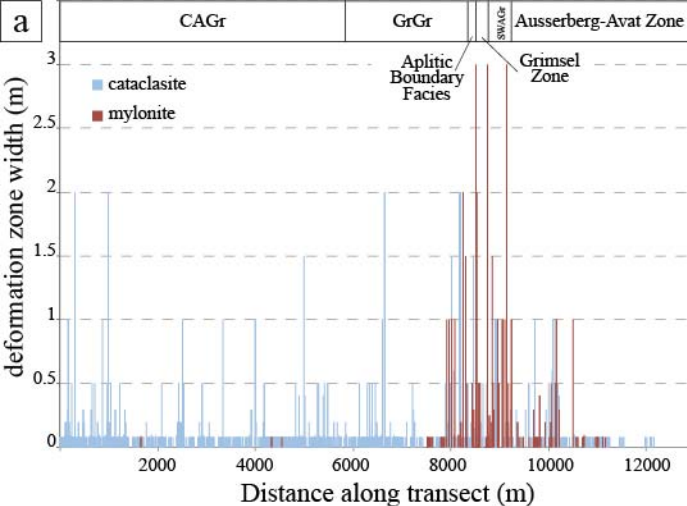


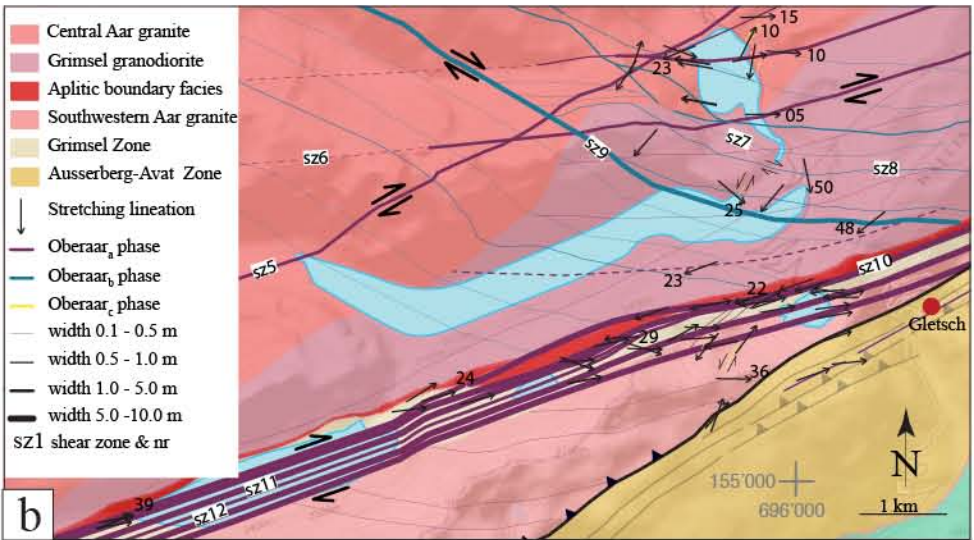
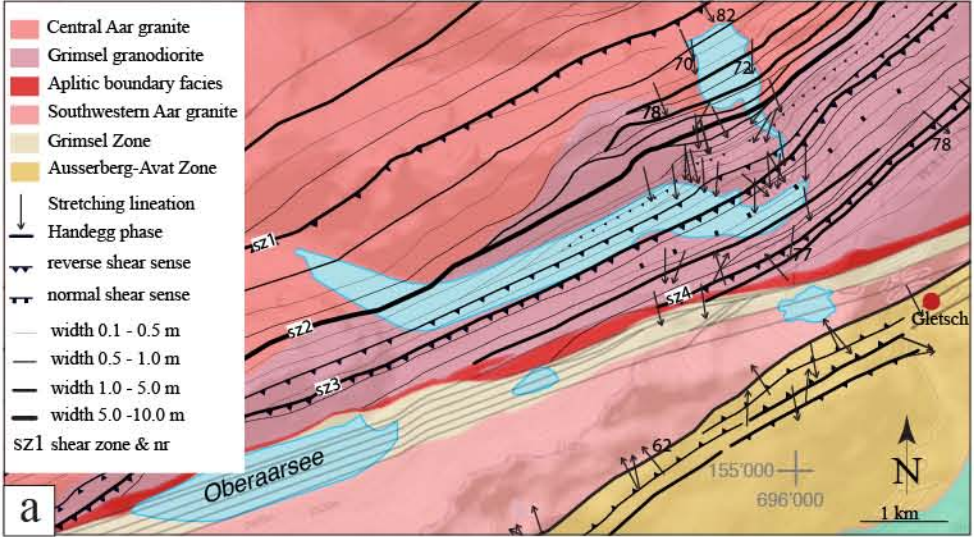










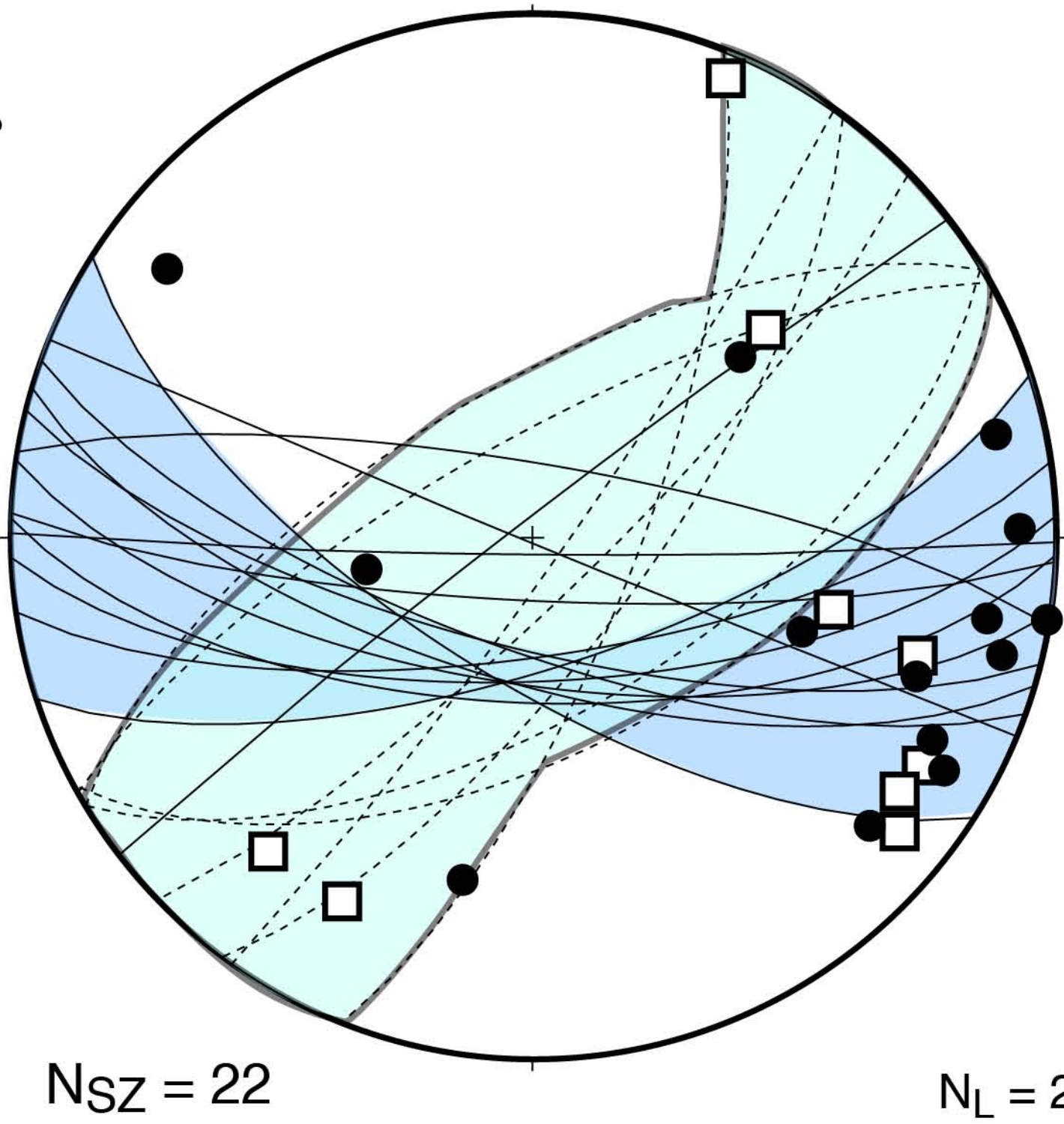
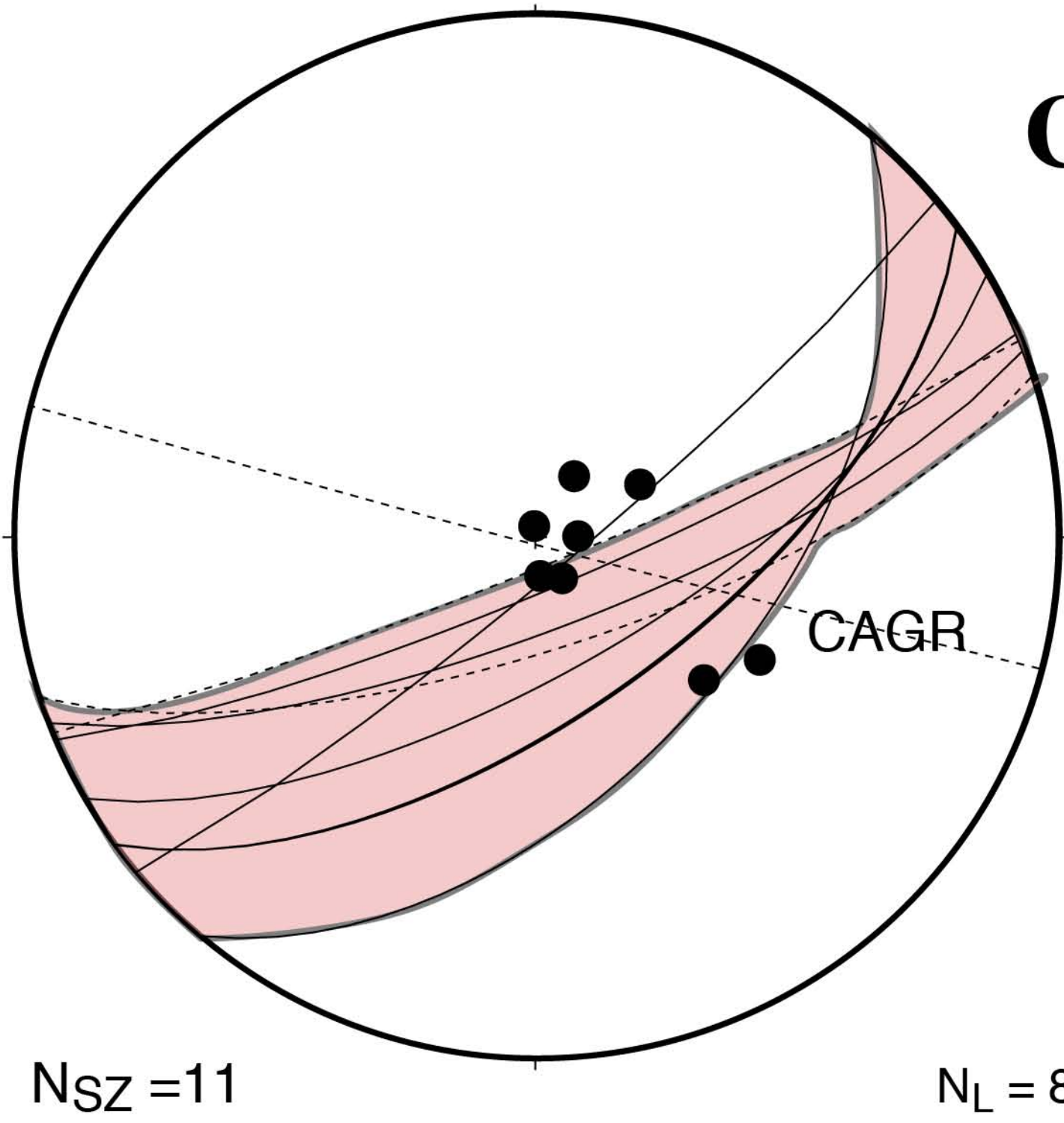




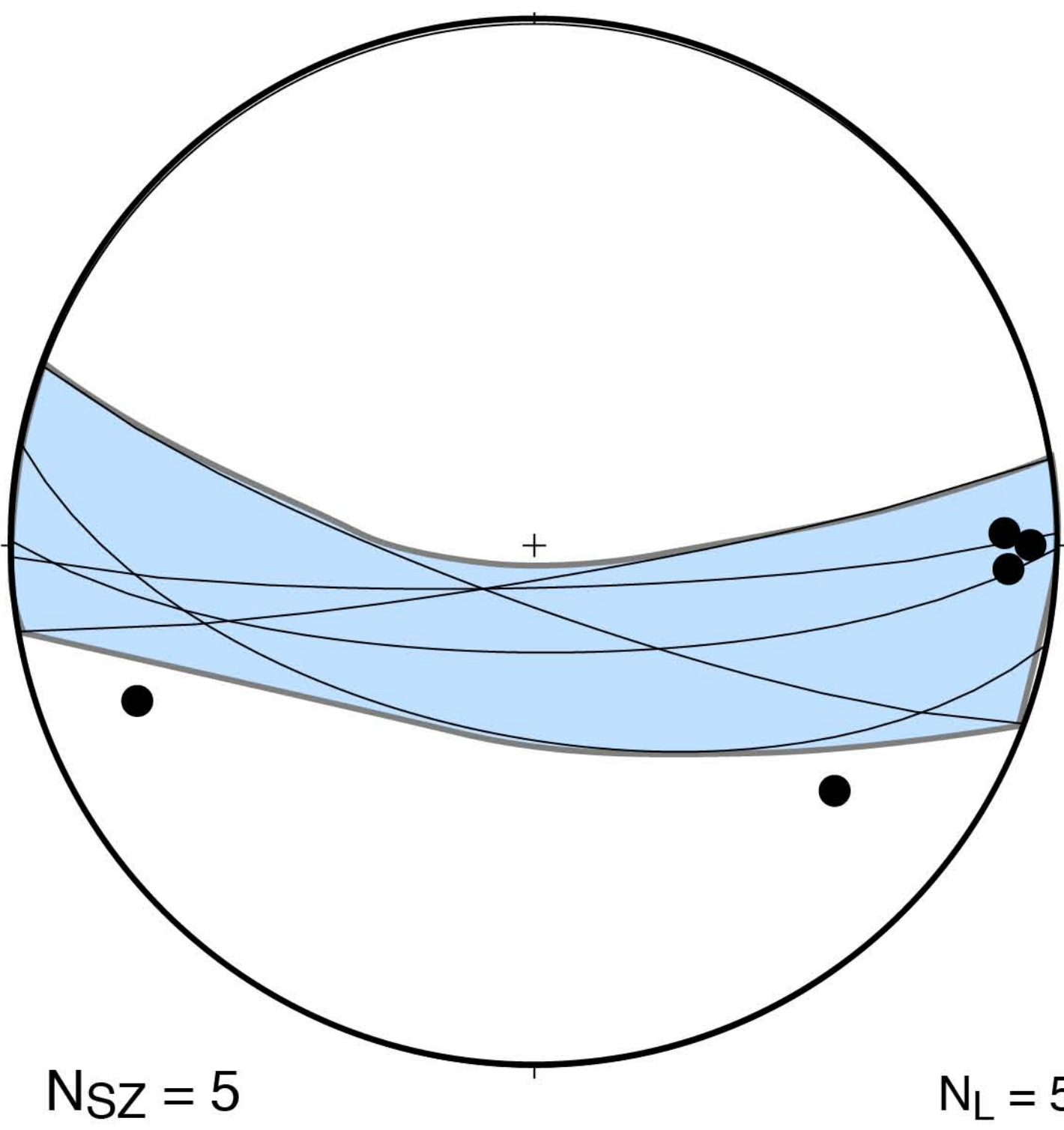
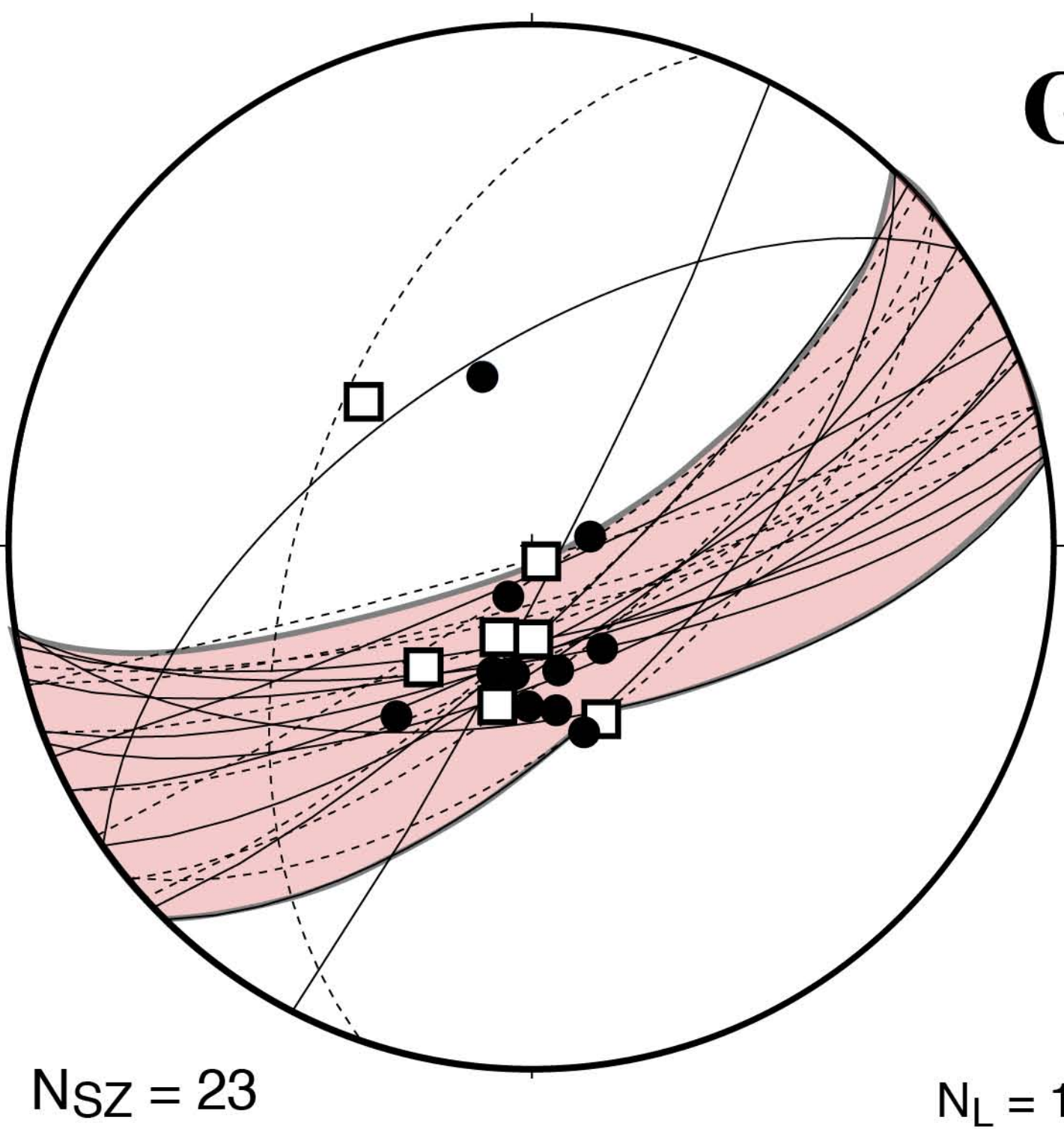
**Handegg phase**  
reverse-normal shearing

**Oberaar phase**  
strike-slip shearing

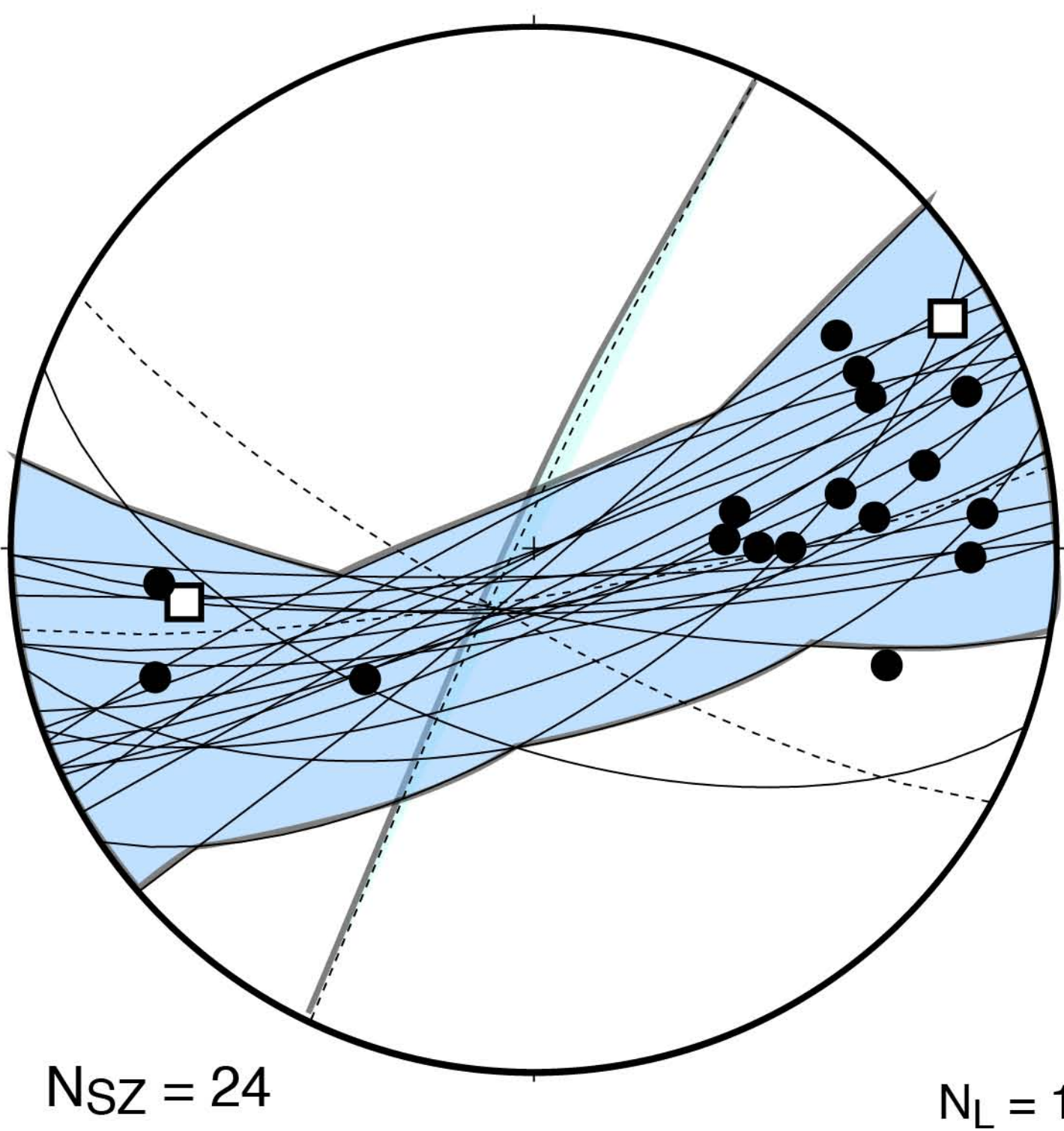
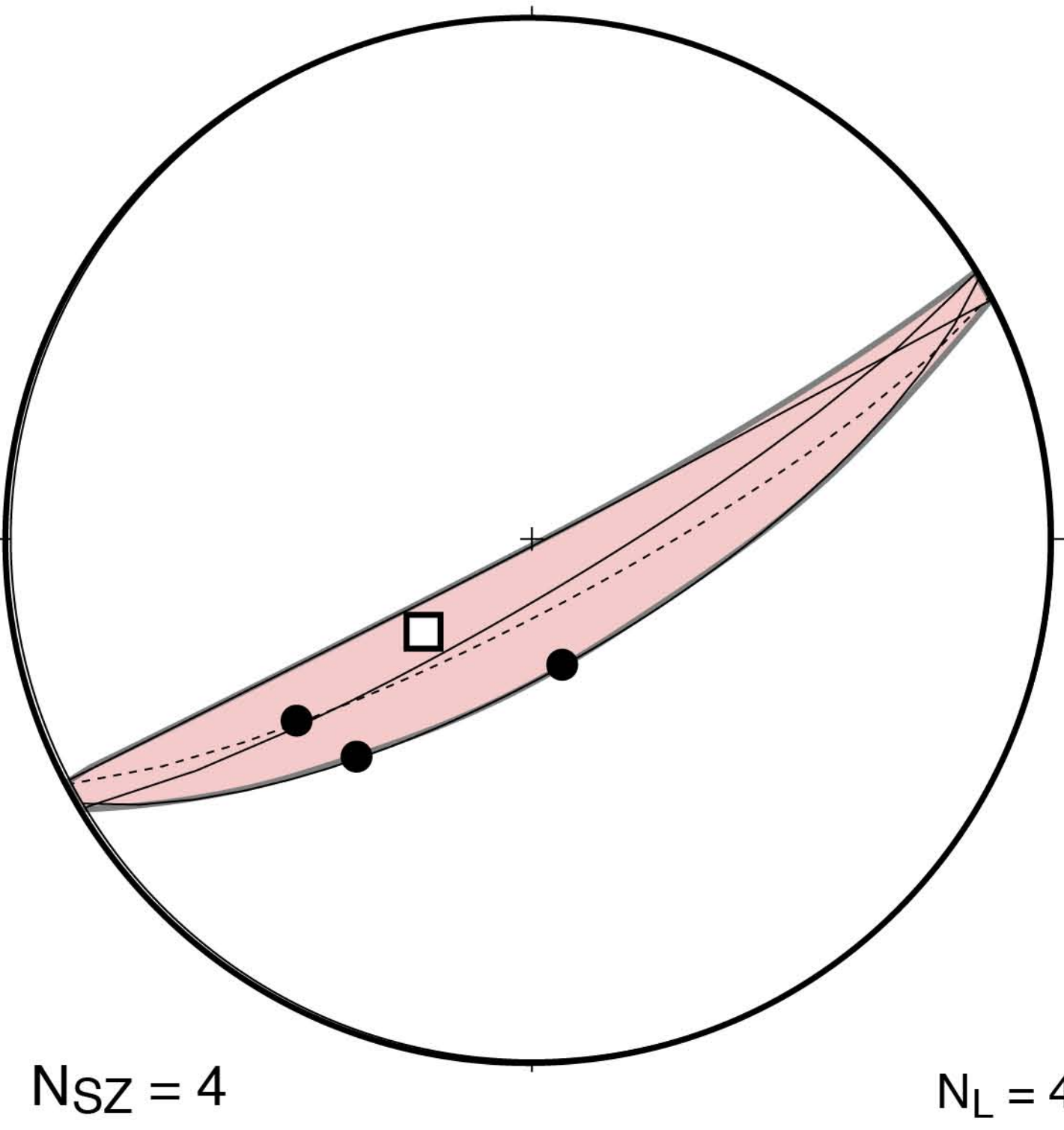
**CAGr**



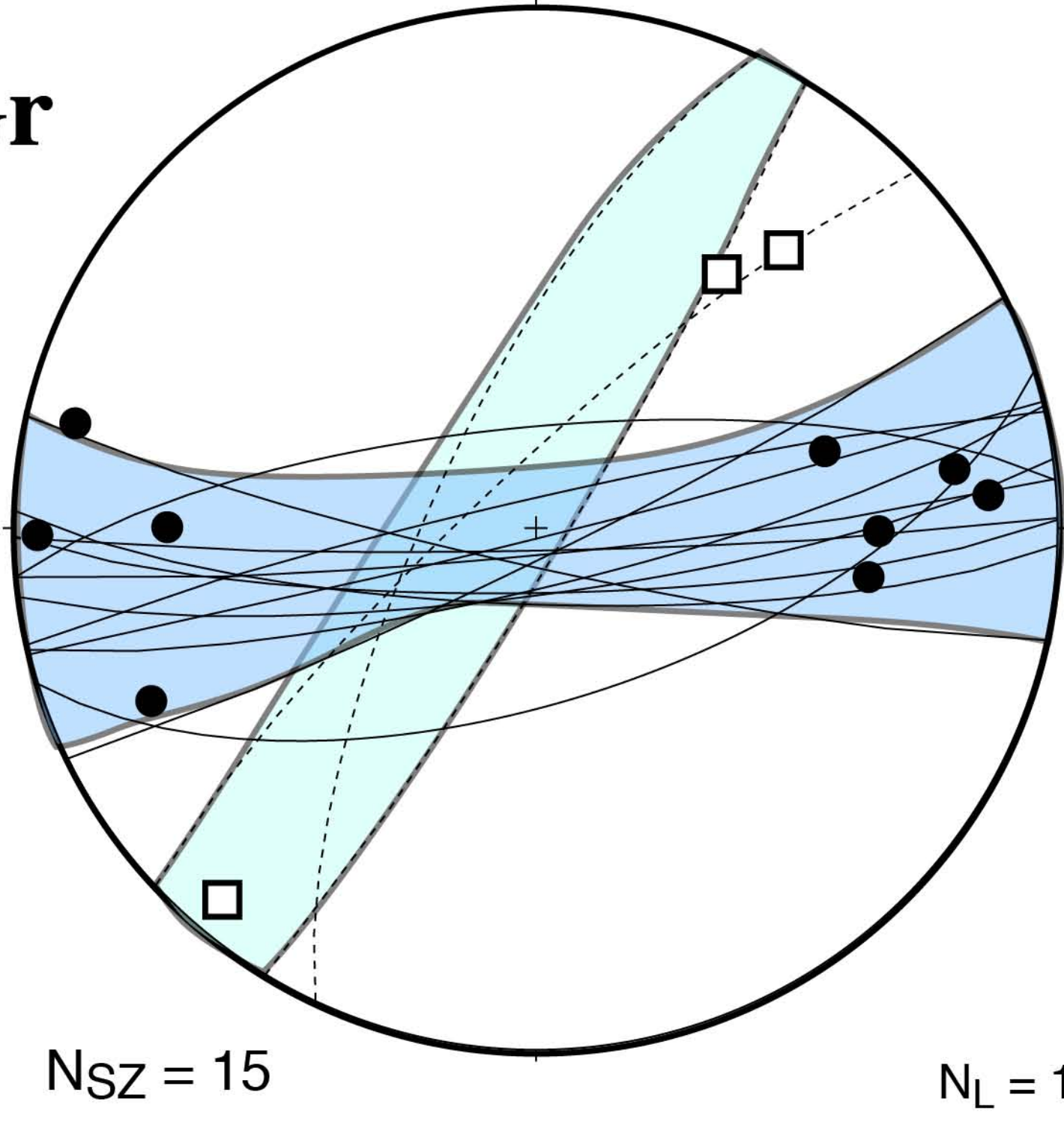
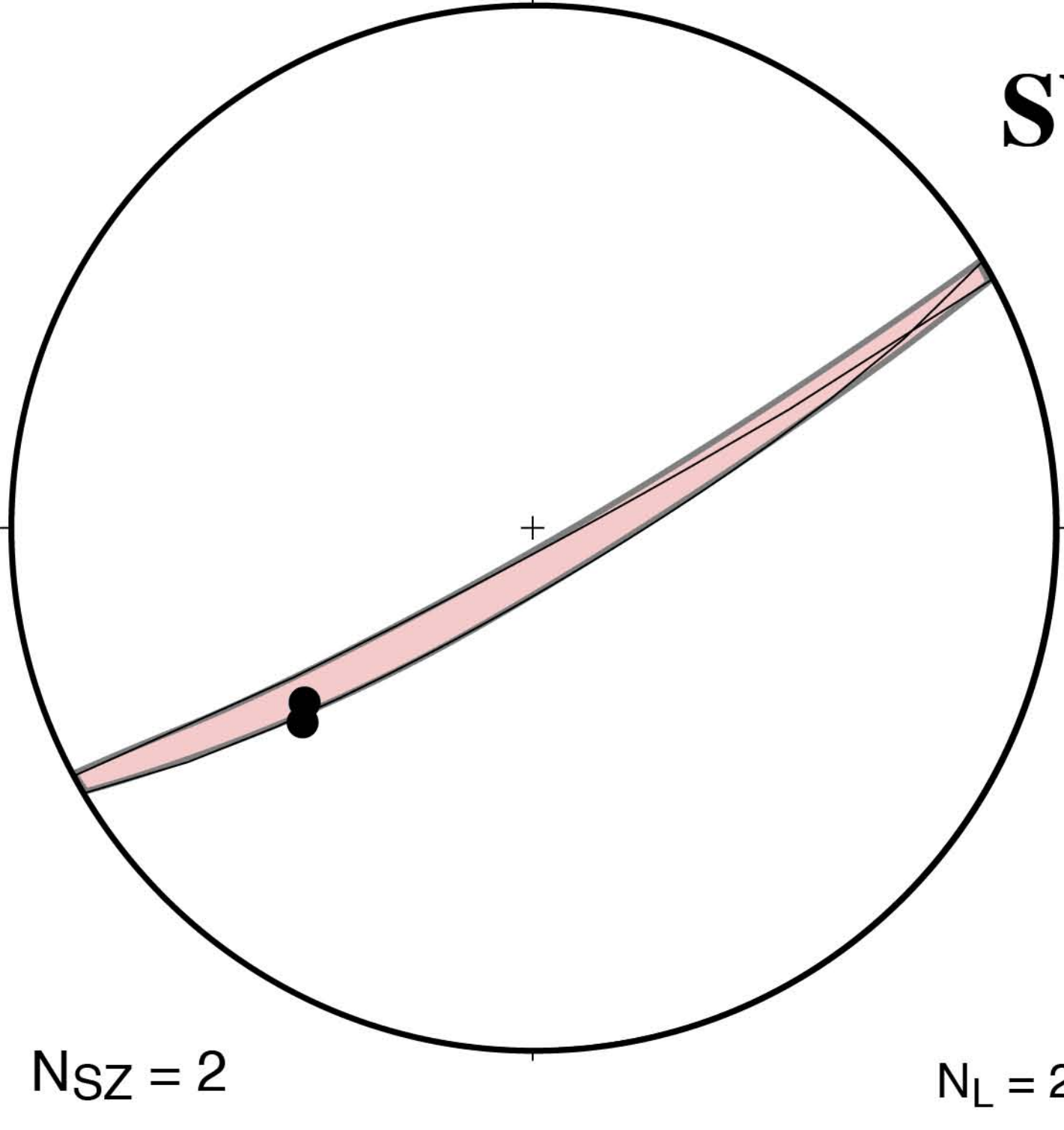
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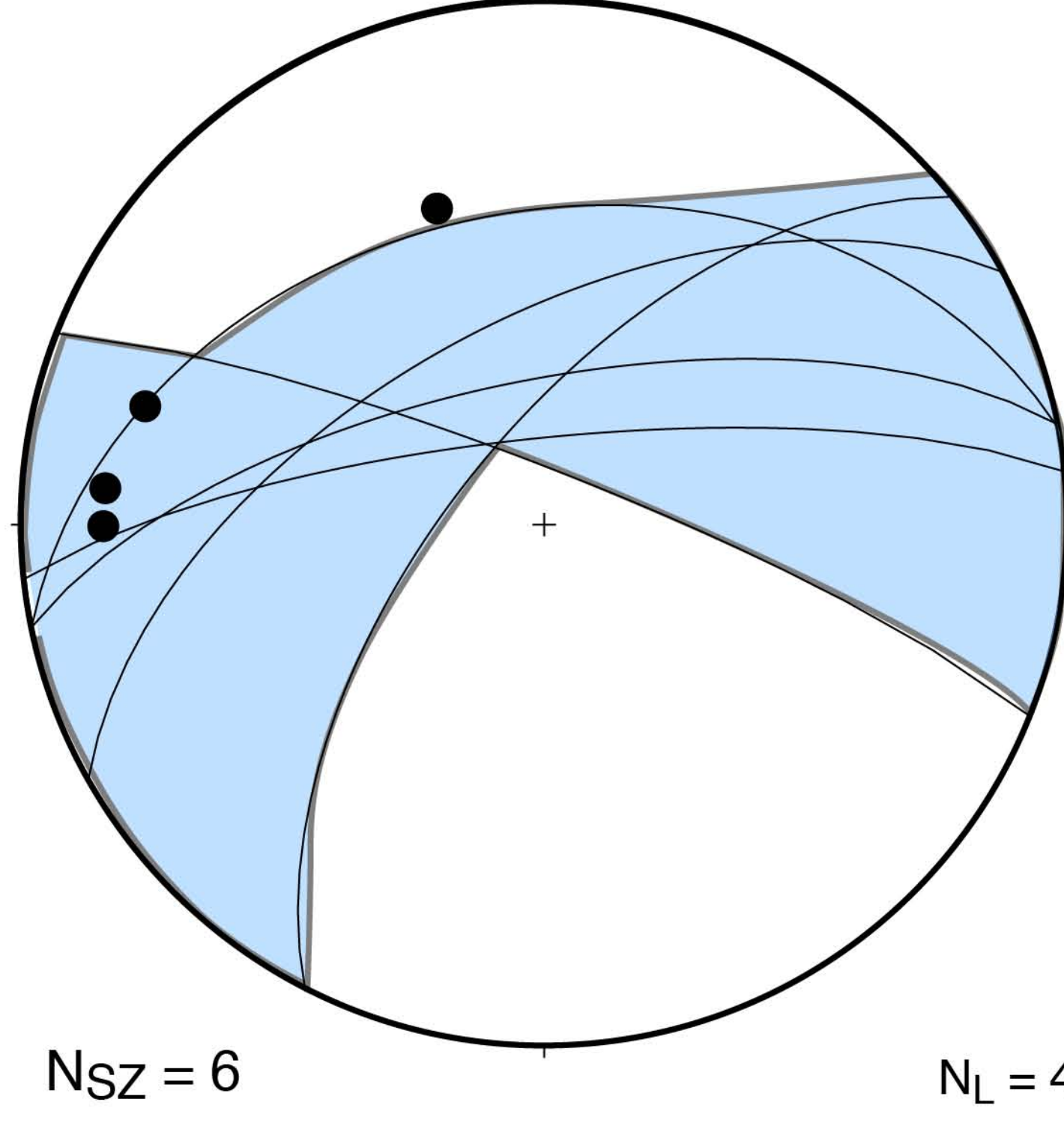
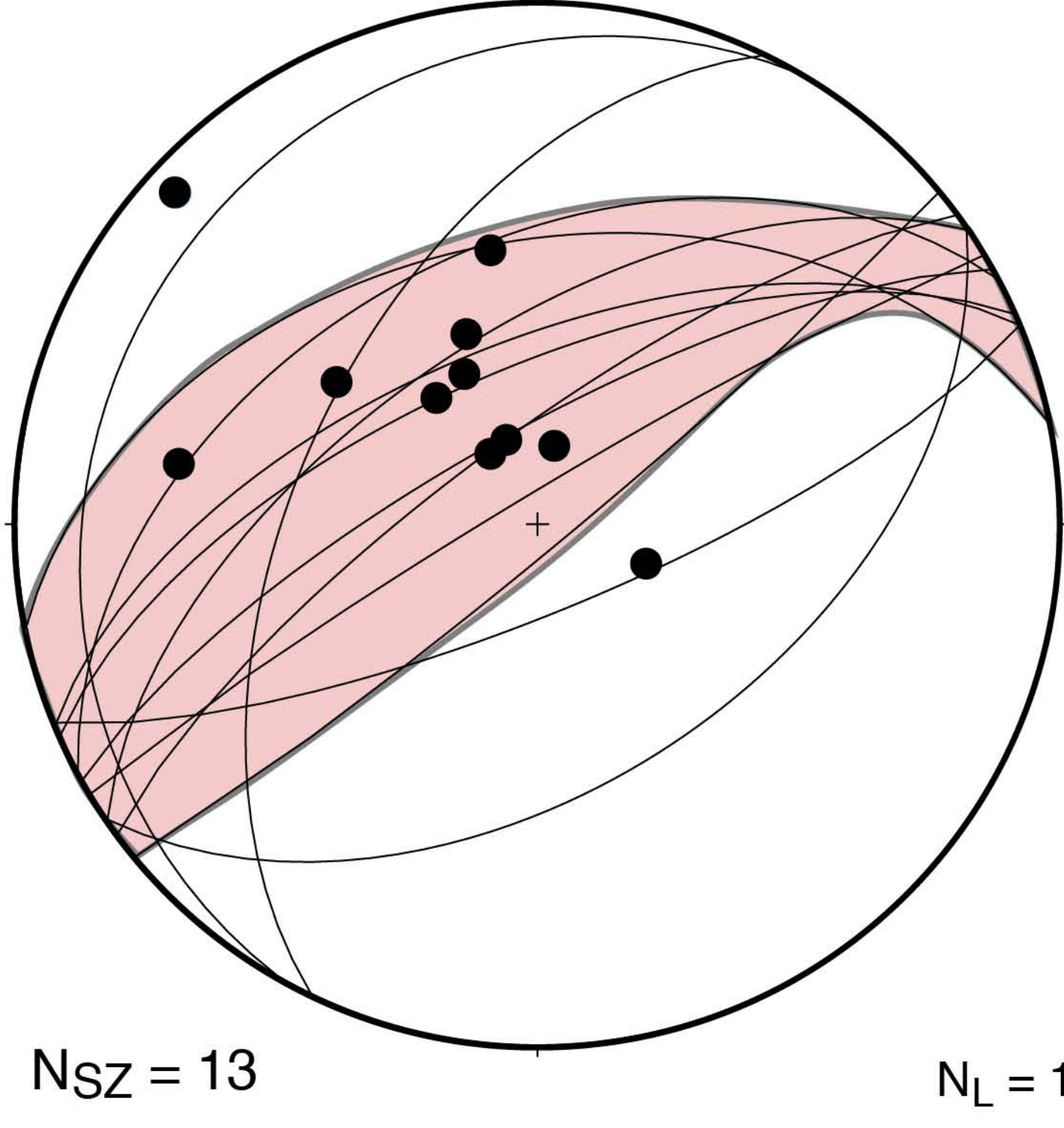
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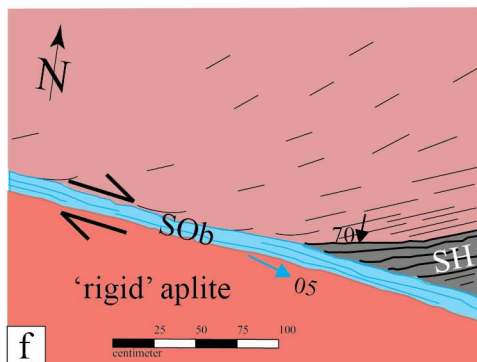
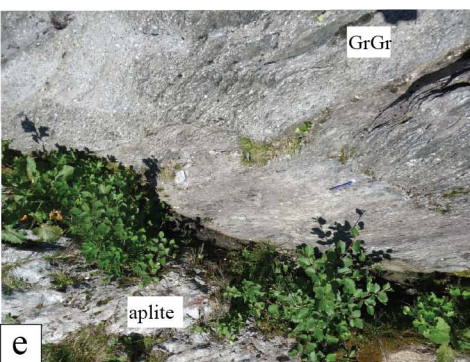
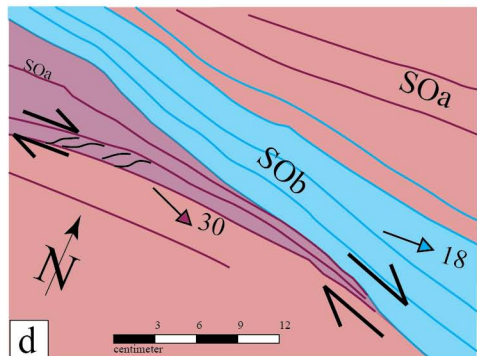
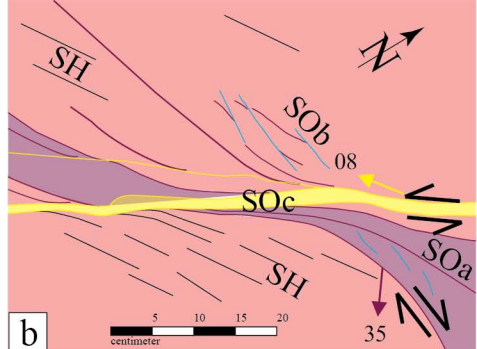
**SWAGr**

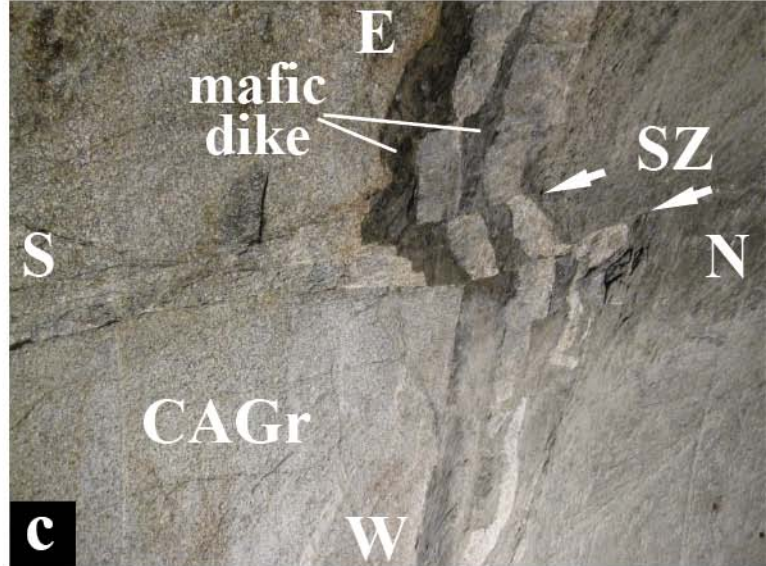


**AAZ**









Supplementary Figure



## Captions of supplementary figures

### Fig. A

Photograph showing km-scale steep, S-dipping Handegg phase shear zones (red lines) in the Alplistock-Ärlenhoren area (665°000/161°000). Note the major shear zones being connected by shorter secondary ones.

### Fig. B

Handegg phase shear zones in aplitic boundary facies at the outcrop scale (locality: 668°942/157°321). (a) Steep S-dipping main set of Handegg shear zones (hanging wall up toward N) being interconnected by secondary set of steep N-dipping Handegg shear zones with opposite sense of shear (hanging wall up toward S). (b) and (c) indicate positions of corresponding figures. (b) Steep main Handegg shear plane with stretching lineations, rotating from down dip to an oblique slip, documenting the transition from reverse Handegg phase to oblique Oberaar phase shearing. (c) Steep secondary N-dipping Handegg phase shear plane with hanging wall up toward S sense of shear. Fieldbook (20x13 cm) and pen (diameter 7 mm) as a scale.

Fig. C. Handegg phase shear zones in aplitic boundary facies at the outcrop scale (locality 668°934/157°341). (a) overview image showing two subvertical mylonitic main shear zones (1,2) being connected by secondary mylonitic shear zone branches (3, 4). Main and secondary shear zones form a conjugate set with opposite shear senses. Orientations of shear planes and stretching lineations of (1) and (2) are (Sz1: 347/88, Sz2: 195/87) and (SL1: 295/63, SL2: 277/73), respectively. Orientations of shear planes and stretching lineations of (3) and (4) are (Sz3: 342/70, Sz4: 355/66) and (SL3: 302/66, SL4: 321/56), respectively. (b) Enlarged view of (a) showing the mylonitic foliation within the Handegg phase secondary shear zone branch (4) Fieldbook as a scale, 20x13 cm.

### Fig. D

Crosscutting relationships between Handegg und Oberaar phase. (a) Large-scale relationship showing NE-SW striking Handegg shear zone (SZ<sub>Ha</sub>) being cut by younger Oberaar phase shear zones (large-scale dextral Sz10 Oberaar<sub>a</sub> (SZ<sub>Oba</sub><sub>a</sub>) and dextral Oberaar<sub>b</sub> (SZ<sub>Oba</sub><sub>b</sub>)). Image shows area around location 668°000/158°000. (b) Bird's eye view of a granodiorite dissected by an aplite dyke (Ap) with pervasive Handegg phase foliation (S<sub>Ha</sub>) all being cut by a dextral Oberaar<sub>a</sub> (SZ<sub>Oba</sub><sub>a</sub>) shear zone. (c) Enlarged detail from (b) illustrating the presence of a 1cm wide mylonitic fabric in the Oberaar<sub>a</sub> (SZ<sub>Oba</sub><sub>a</sub>) shear zone. Outcrop locality: 669°250/157°275.

### Fig. E

Crosscutting relationship Handegg phase and Oberaar<sub>c</sub> shear zone. (a) Sinistral Oberaar<sub>c</sub> shear zones crosscutting at high angle a W-E striking metabasic dyke (mbd, nagra Grimsel Test Side). (b) E-W striking Metabasic dyke being being strongly deformed during Alpine shearing. (c,d) Bird's eye view of Grimselgranodiorite and aplite dykes (Ap) with pervasive Handegg phase background foliation (S<sub>Ha</sub>) being dissected by a sinistral Oberaar<sub>c</sub> strike-slip shear zone (SZ<sub>Obc</sub>). (c) overview figure

with 8 cm long pocket knife as scale. Inset shows position of enlargement in (d). Outcrop locality: 668'150/157'140.

Fig. F.

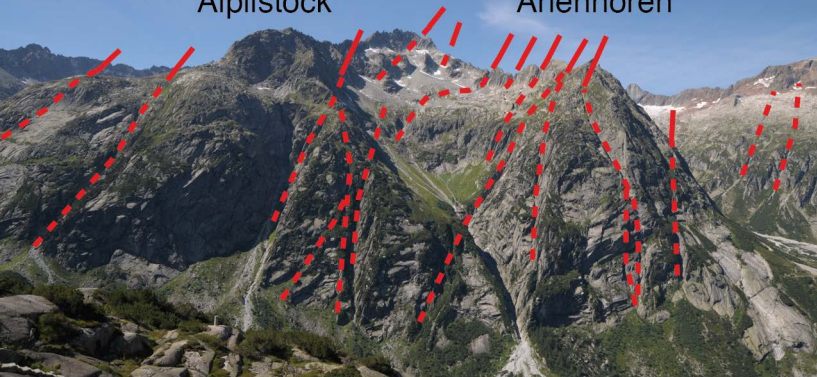
Compilation of shear plane orientations, stretching lineations and shear senses for Handegg and Oberaara-c structures collected within a one kilometer wide stripe parallel to the profile section P-P' (for location of profile trace see F in Fig. 7b). (a) Vertical cross section with major shear zones (grey and rock types). (b) Geological map with plunge azimuth of stretching lineations. (c) Changes in plunge for the different stretching lineations. (d) Changes in dip azimuth of the different shear planes. CAGr: Central Aar granite, GrGr: Grimsel granodiorite, APF: aplitic boundary facies, GZ: Grimsel zone, SWAGr: southwestern Aar granite, AAZ: Ausserberg-Avat zone, GSPZ: Grimselpass shear zone.

S

N

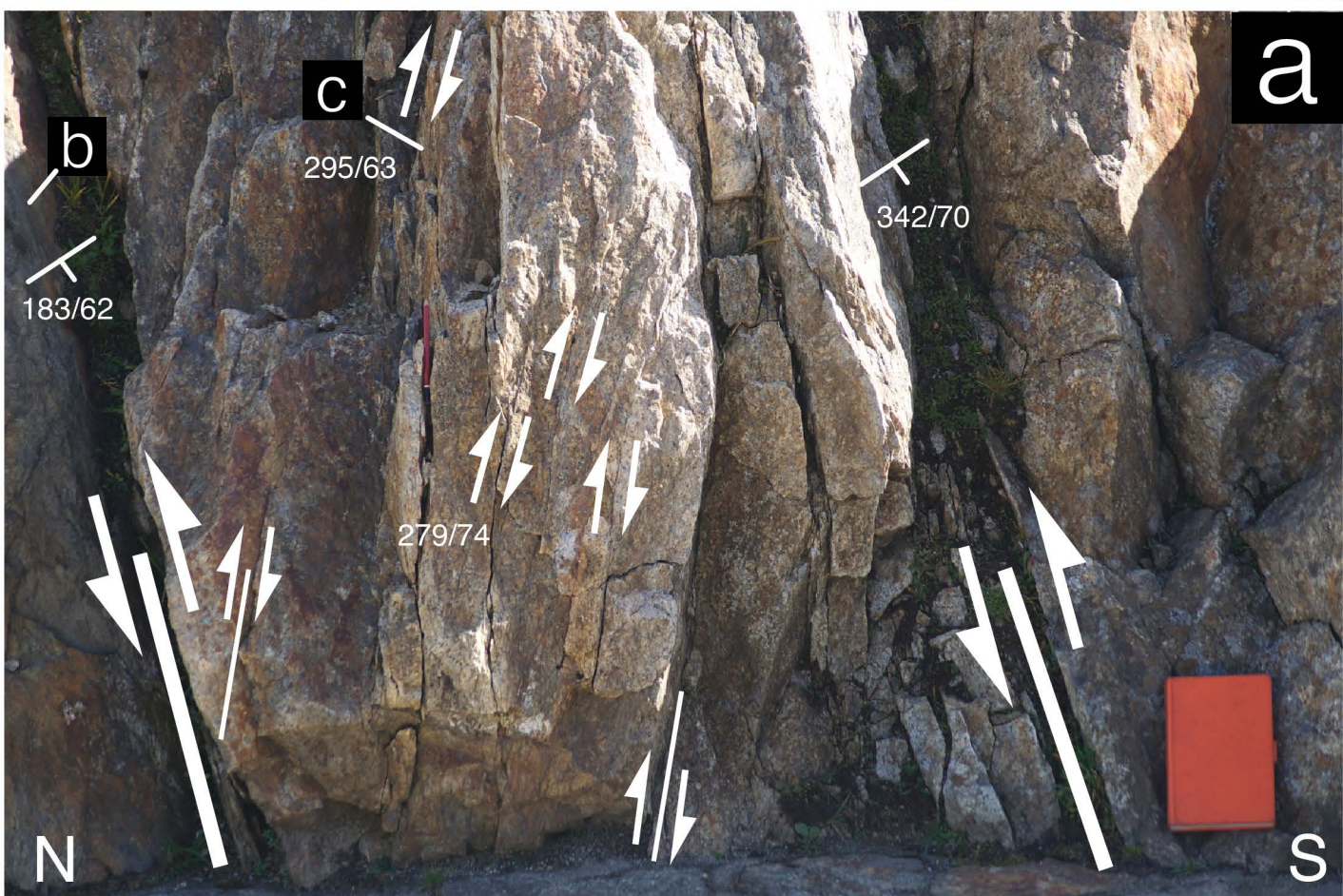
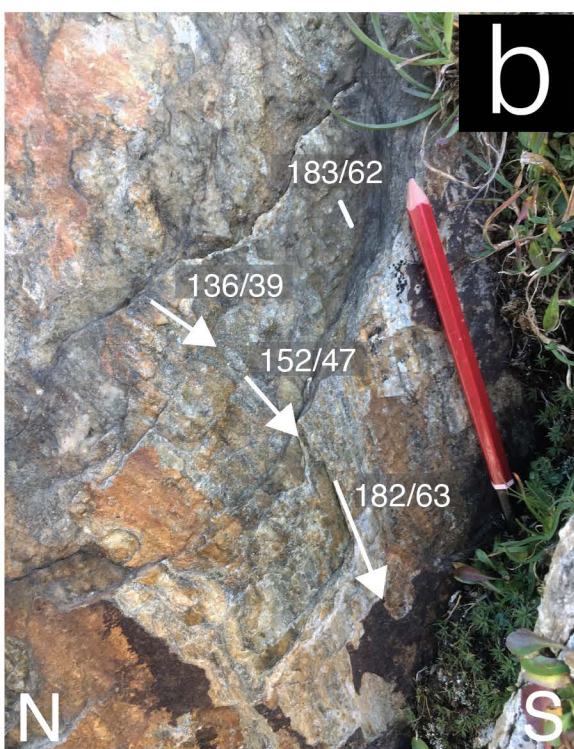
Alplistock

Ärlenhoren



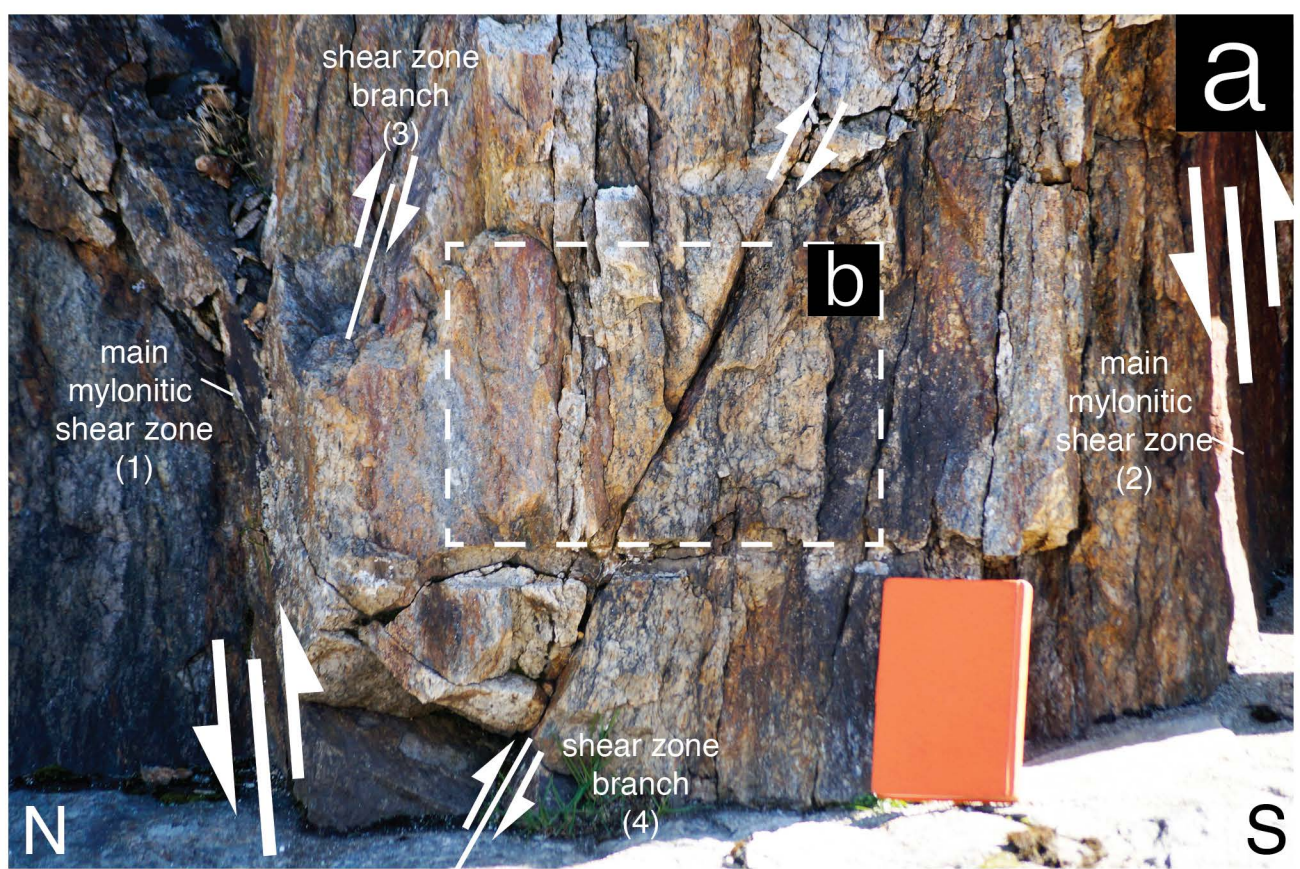
Supplementary Fig. A





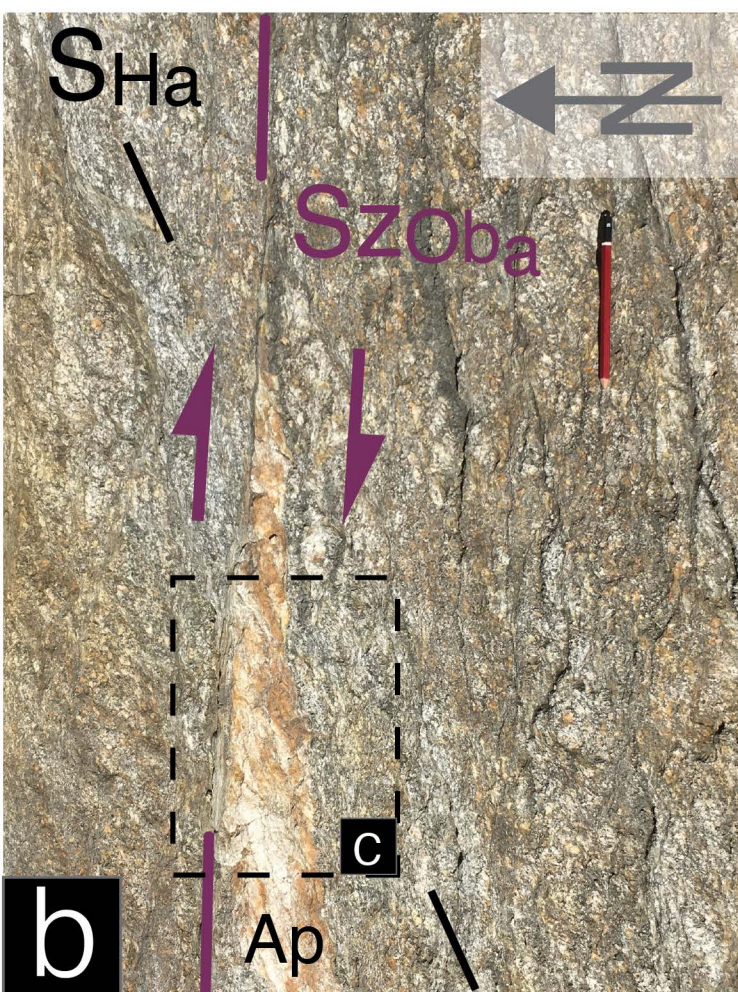
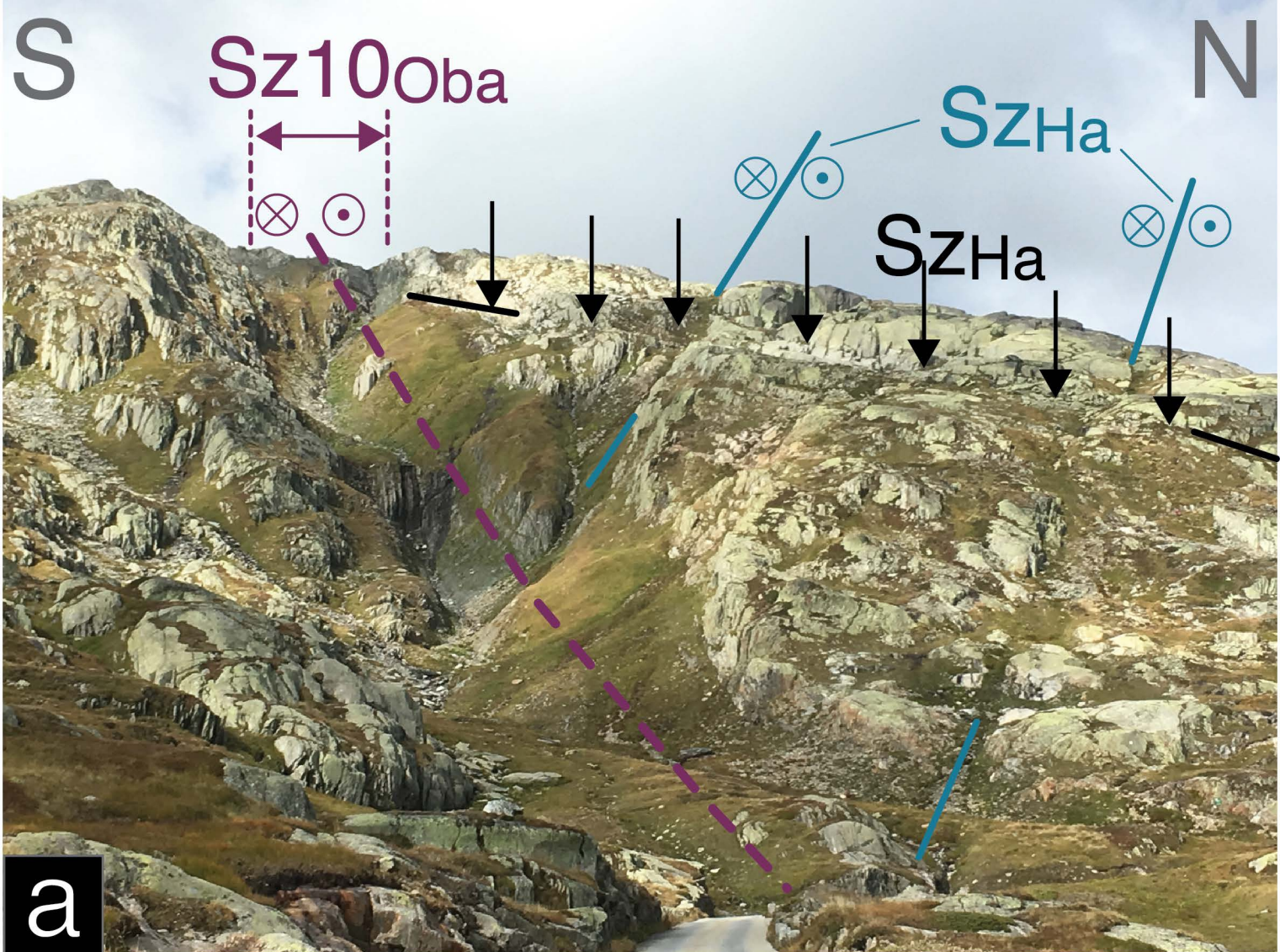
Supplementary Fig. B





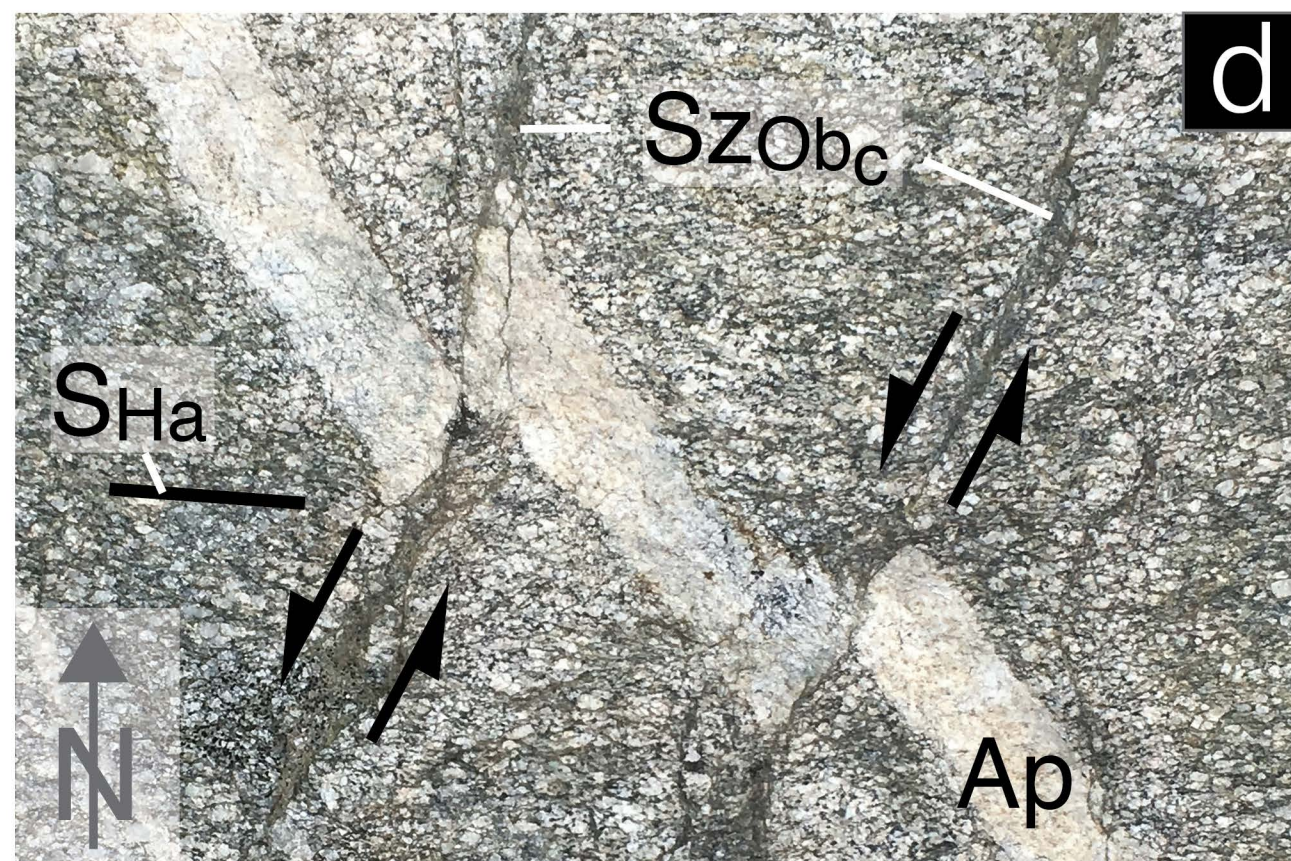
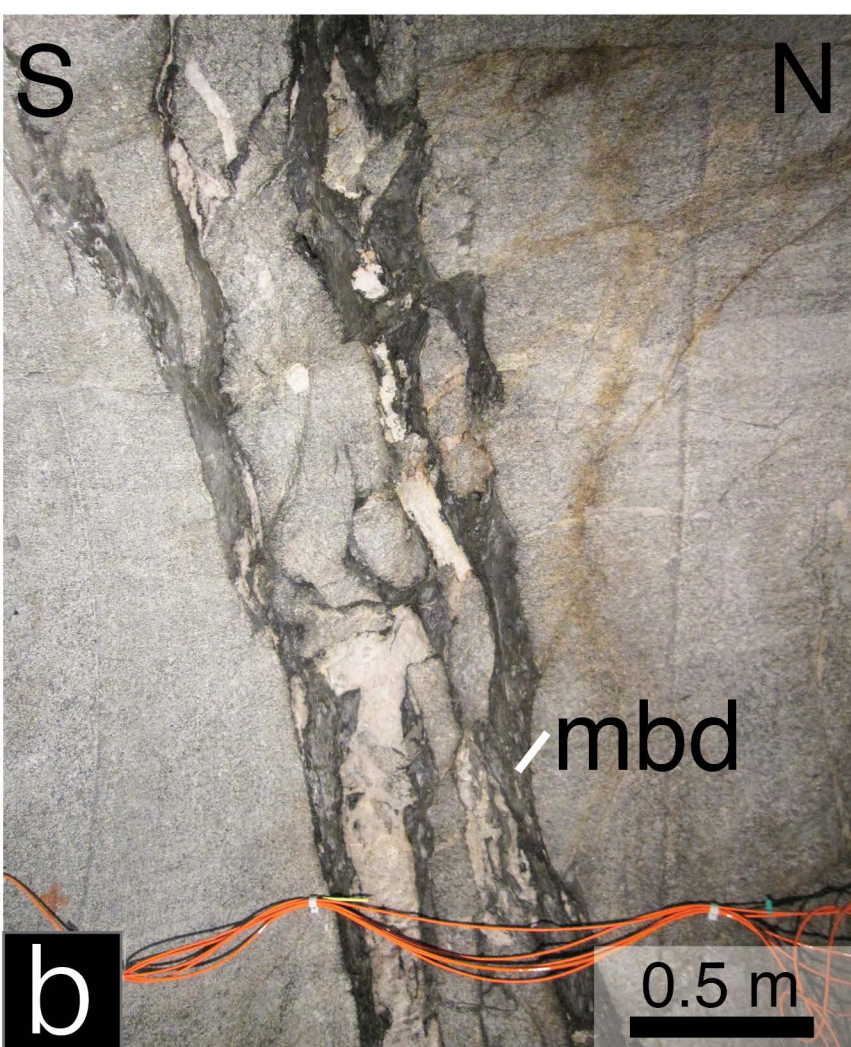
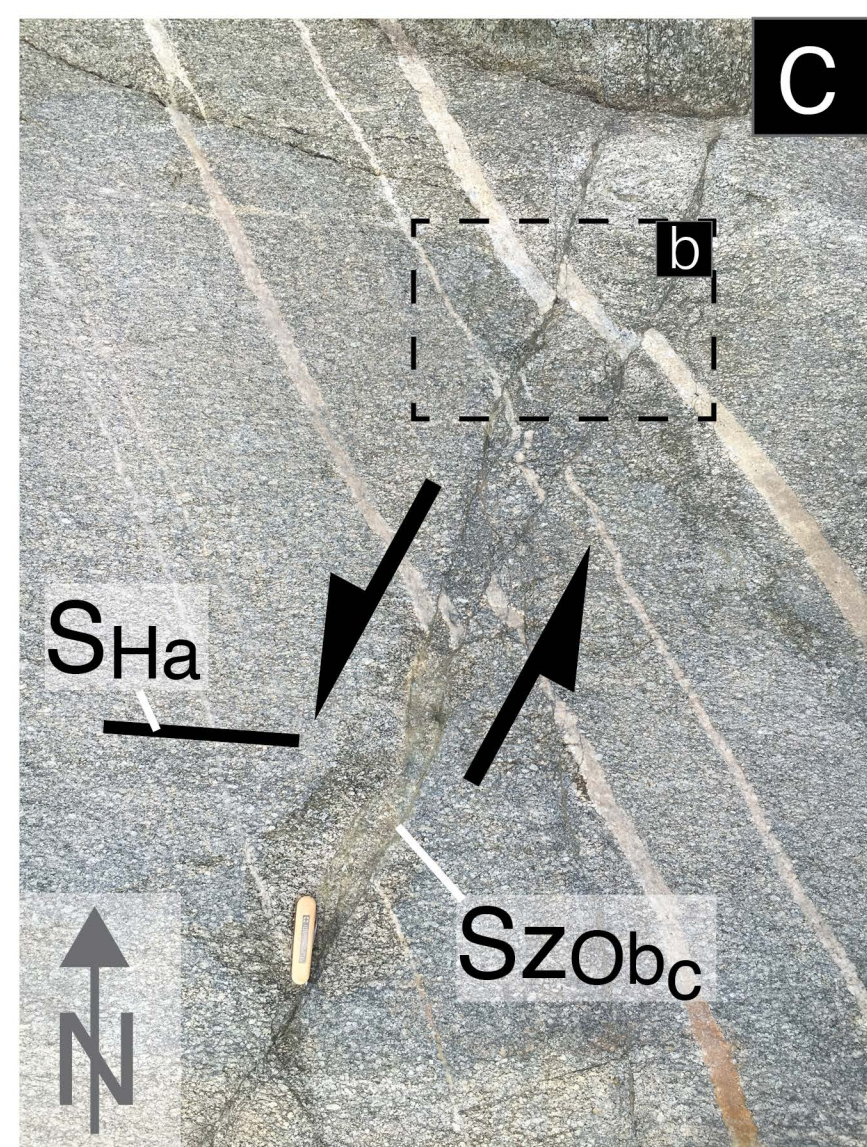
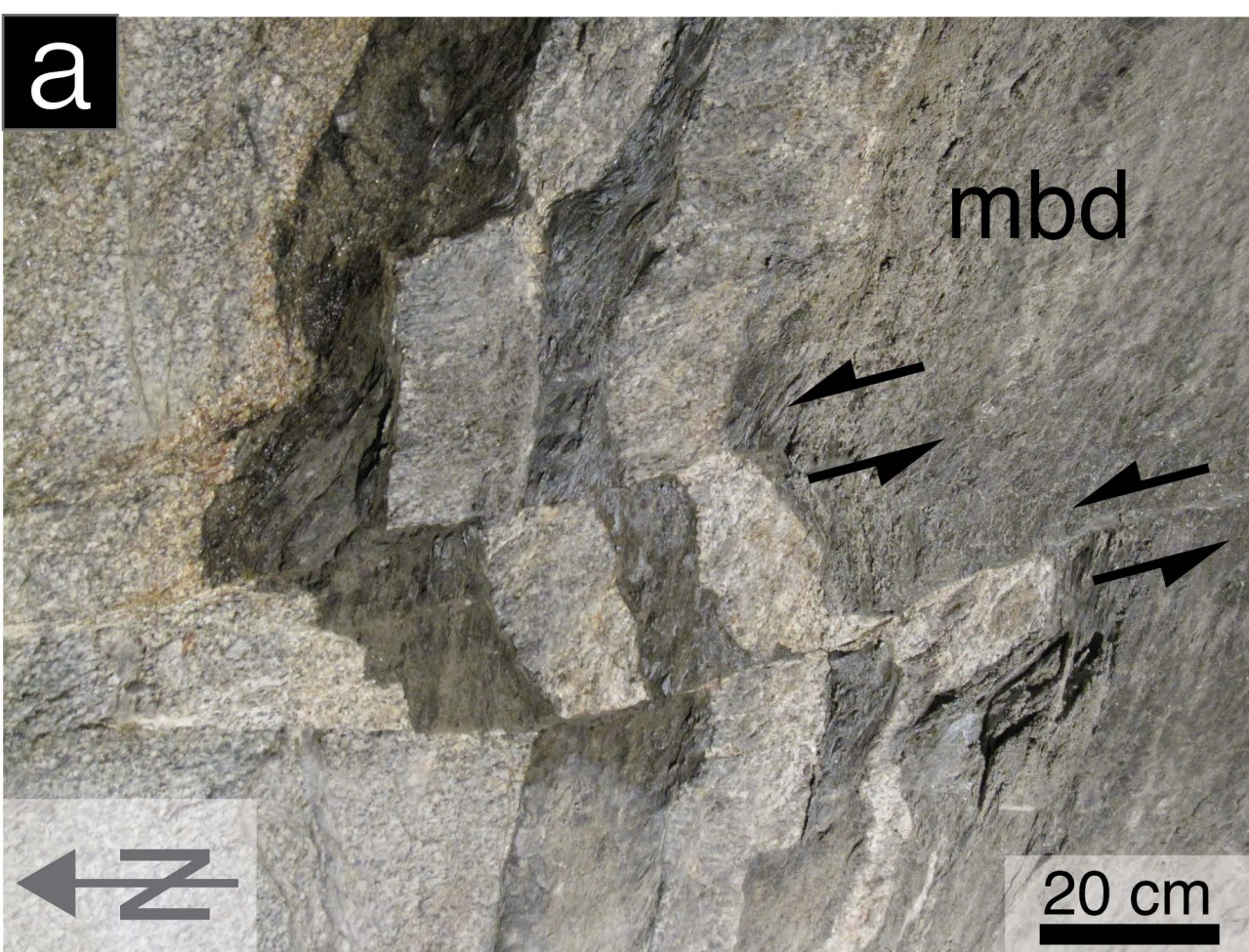
Supplementary Fig. C





Supplementary Fig. D





Supplementary Fig. E



